Comet Chemistry: Obtaining Clues to the Formation and Evolution of the Solar System with High-Resolution Infrared Spectroscopy

Neil Dello Russo, Harold A. Weaver Jr.,
Carey M. Lisse, and Ronald J. Vervack Jr.

Comets are icy leftovers from the formation of the solar system about 4.5 billion years ago. Because they have been stored at cold temperatures and their interiors have been protected by an overburden of insulating layers, comets contain the most unaltered remnants from the birth of our solar system. For this reason, determining their chemical composition and physical properties is a fundamental problem in planetary science that can provide clues to the temperature, chemistry, and radiation environment present in the early solar system. Recent technological advances have enabled the sensitive determination of the chemical inventories in an increasing number of comets using high-resolution IR spectrometers at ground-based observatories. To date the diversity in chemical composition within the comet population has been remarkable, providing our first detailed look at the "fossil record" of the early solar system.

INTRODUCTION

Comets likely formed in the early solar nebula at distances far enough from the Sun to condense water ice—from about 4 to 5 astronomical units (AU) out to at least 50 AU from the Sun (1 AU = the distance from the Sun to Earth, which is about 93 million miles). In the traditional view, comets that formed in the giant planets region of the solar nebula between the orbits of Jupiter and Neptune were almost completely removed from this area owing to gravitational interactions with the gas giants. While many of these comets collided with the giant planets or their moons, some were ejected toward the inner solar system where they impacted the Sun and the inner planets, including Earth. In this way, comets are believed to have provided a significant amount of raw materials to the early Earth, with the water contributing to the formation of the oceans, while other volatile ices and organic material within dust grains comprised the precursor chemicals needed for the origin of life.[1] Other comets formed in the giant planets region were ejected out to great distances and formed the Oort

cloud, a spherical reservoir of comets thousands of astronomical units from the Sun. On the other hand, comets that formed outside the orbit of Neptune are thought to have remained near the plane of the solar system close to their formation region. These comets make up a reservoir known as the Kuiper Belt. Because temperatures and radiation doses varied significantly with distance from the young Sun, conditions were likely quite diverse in the comet-forming regions of the early solar nebula (Fig. 1). It would be surprising if the chemistry of the comet population did not reflect that diversity.

In general, the brightest visible comets such as C/1995 O1 Hale-Bopp and C/1996 B2 Hyakutake are Oort cloud comets and can be recognized as such by their long periods and randomly inclined orbits. Short-period comets with orbits nearly in the plane of the solar system are predominantly of Kuiper Belt origin, although a few may be highly evolved Oort cloud comets. Short-period comets have usually experienced more close approaches to the Sun than their Oort cloud counterparts, so in addition to having different formative regions, they also have different evolutionary histories. Evolutionary effects are most important in the outer layers of a comet (on the order of meters from the surface), while the interior of the nucleus, protected by an overburden of surface layers, should largely be pristine except for perhaps the most volatile ices.[2] Sampling the chemical composition of a comet as a function of depth in the nucleus can therefore potentially provide a means of distinguishing the effects of evolutionary processing from primordial chemistry.

Relating the diversity of comet chemistries to specific nebular formation regions has been elusive. The distinction among different nebular formation regions is likely blurred by significant turbulent mixing of materials from the inner and outer solar nebula[3,4] and by the migration of the giant planets[5] (Fig. 1). Furthermore, although comets are stored in cold environments, their chemical composition (primarily in their outer layers) is not completely unaltered during their lifetimes and evolves during their long storage within the Oort cloud or Kuiper Belt reservoirs[6] (Fig. 1). Perturbations experienced by comets over time can eventually cause them to escape their reservoirs into orbits that approach closer to the Sun, where they are subjected to solar radiation that causes further alterations near their surfaces. When comets get sufficiently close to the Sun, material is lost as a result of sublimation of their volatile ices, releasing gas and dust into a temporary atmosphere called a coma (Fig. 2).

THE IMPORTANCE AND LIMITATIONS OF COMET MISSIONS

The best means of determining the composition of a comet is directly sampling the nucleus and either analyzing the sample with *in situ* instruments or, ideally, returning the sample to Earth for analysis. Returning an unaltered cometary sample containing both volatile and nonvolatile components via a cryogenic sample return and analysis mission is a high priority for solar system exploration. Such a mission would probably require
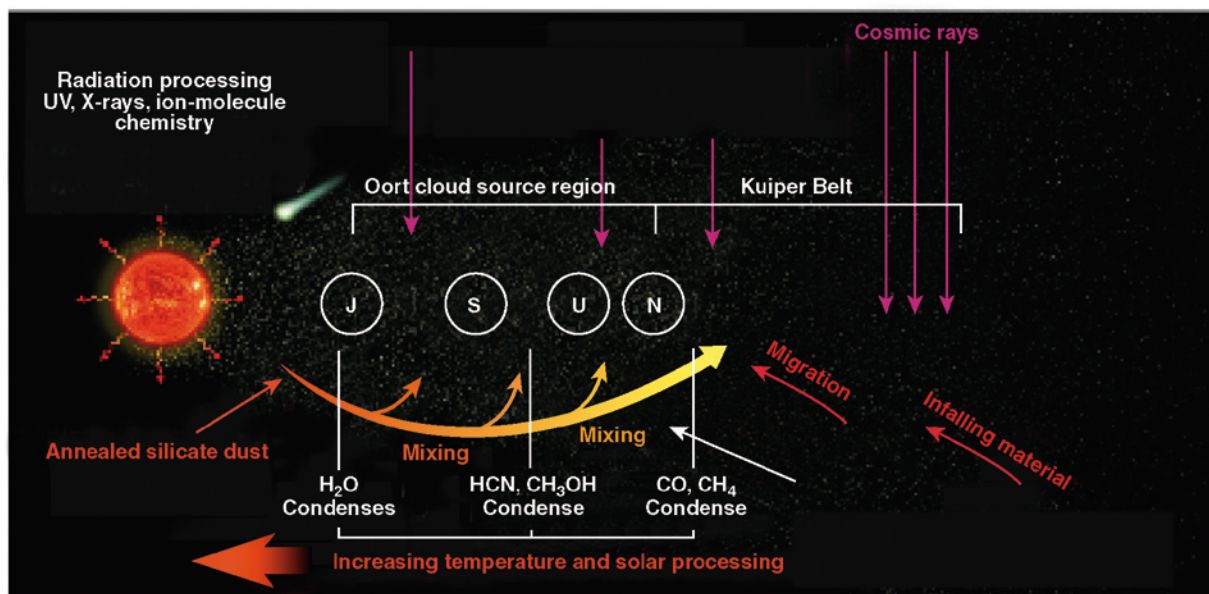

Figure 1. Many processes influence comet composition, including temperature, radiation environment, and degree of mixing in the formation regions. Comet chemistry can also be altered during residence in the Oort cloud or Kuiper Belt and through close passage to the Sun upon release from these reservoirs. Assessing the importance of these processes is a fundamental goal in cometary science. The relative distance from the Sun of the giant planets Jupiter (J), Saturn (S), Uranus (U), and Neptune (N) are indicated.

landing on (or at least touching) the surface of a comet and gathering both surface and subsurface samples to return to Earth. Despite the scientific importance, the complexity and cost of a mission of this type would likely require decades before it is accomplished.
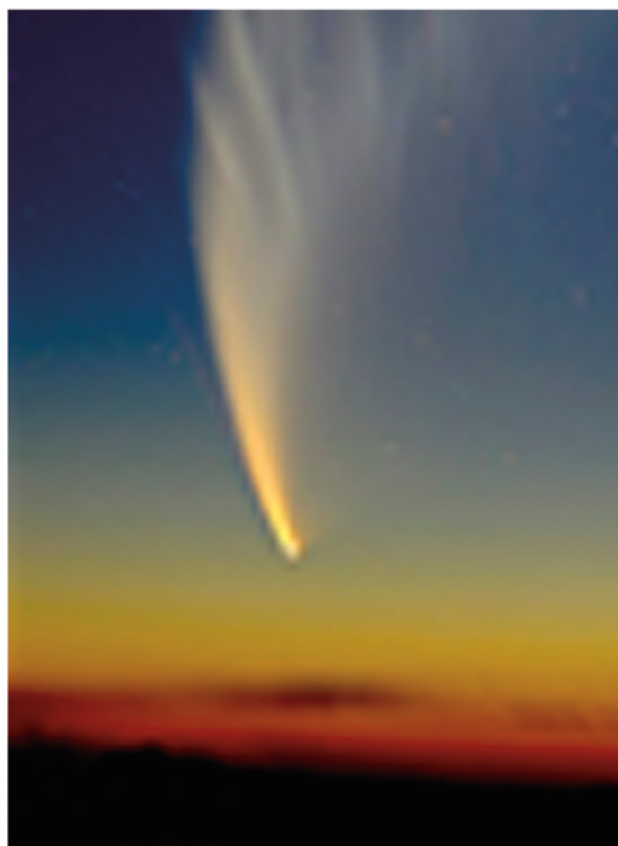

Figure 2. (Top) Comet C/1995 O1 Hale-Bopp showing a prominent white dust tail and blue ion tail (photo courtesy of Drew Sorenson). (Bottom) Comet C/2006 P1 McNaught showing a prominent and striated dust tail (photo courtesy of Gordon Garradd, Loomberah, Australia; http://www.ozemail.com.au/~loomberah/mcnaught.htm).

However, recent missions have revealed detailed information about individual comets that is unattainable using remote sensing techniques and have set the stage for returning a pristine ice and dust sample from a comet.

The Deep Impact Mission rendezvoused with comet 9P/Tempel 1 on 4 July 2005, releasing a 50-kg projectile that impacted the comet.[7] A main goal of the mission was to penetrate the outer processed layers and release material from the pristine interior. A comparison of pre- and post-impact coma compositions could reveal information about the pristine chemistry and processing history of 9P/Tempel 1. In addition to *in situ* observations made by instruments on the spacecraft, a massive Earth-based campaign was initiated to observe the effects of the impact.[8] This coordinated campaign with Earth-based observers was an important aspect of the mission because obtaining synchronized observations of a comet at multiple wavelengths is rarely possible. The experiment was a success, as the impact revealed information on the subsurface structure and composition of 9P/Tempel 1. Unfortunately, obscuration by ejected material did not allow the observation of the impact crater, so the depth to which material was excavated is unknown. Also, the impact event did not open a new active area on the comet, so its increased activity was transitory, preventing long-term studies of volatiles and dust released from below the surface.

The recent Stardust Mission flew through the coma of comet 81P/Wild 2, capturing dust particles and returning them to Earth.[9] To minimize the alteration of these dust particles during the high-velocity capture process, a low-density collection medium (aerogel) was used. Analysis of the Stardust samples is revealing unprecedented compositional information on the collected dust, illustrating the power of using state-of-the-art techniques in Earth laboratories to analyze returned samples. Furthermore, samples will be stored for future analysis as analytical techniques improve. However, particles returned from 67P/Wild 2 by Stardust are not completely pristine because the high velocities (about 6 km/s) of the capture process caused heating and alteration in the outer layers of the captured dust. Also, the capture and storage of the samples were not designed to return volatile ice samples from the comet, so little information on the volatile composition of 81P/Wild 2 was returned.

The European Space Agency's Rosetta Mission is on its way to orbit comet 67P/Churyumov-Gerisemenko, and study its composition, structure, and behavior for over a year. Rosetta will also send a lander to the surface of a comet for the first time and analyze samples *in situ*. The duration of the Rosetta mission and the state-of-the-art payload will provide unparalleled information on this comet; however, no samples will be returned to Earth for analysis.

Although comet missions provide unique information on the detailed composition and structure of

individual comets, cost and technological obstacles limit the number and range of objects that can be studied (e.g., the random inclination of their orbits and the unpredictable appearances of Oort cloud comets make them in general poor mission targets). Also, if comets display a great deal of compositional diversity as a group (as expected), samples from individual comets may not be representative of the range of possibilities within the overall population. Thus, comet missions and remote sensing techniques are both necessary and complementary; missions provide ground truth for remote sensing data, while the large number of comets that can be analyzed with remote sensing puts the detailed information returned by missions on a few comets into context. Remote sensing observations are also invaluable in identifying the most interesting targets for future cometary missions.

DETERMINING COMET CHEMISTRY THROUGH GROUND-BASED HIGH-RESOLUTION IR SPECTROSCOPY

Remote sensing techniques can provide a more routine—if less detailed—account of comet chemistry. As comets approach the Sun, their spectra consist of reflected sunlight and thermal emission from dust in the coma as well as emission lines from gas phase coma species excited by sunlight. Thus, the volatile compositions of cometary nuclei have generally been inferred from measurements of the spectral signatures of gases forming the coma. Molecular dissociation fragments have been studied in comets for nearly 100 years.[10] Narrowband photometric studies (the use of narrowband filters at optical wavelengths to isolate light emitted from gas species) have determined the composition of daughter products (species formed within the coma via chemical reactions or from the breakdown of parent molecules released directly from ices in the nucleus) in a large number of comets.[11] However, narrowband photometric techniques sample a limited number of species and the determination of their native ice or dust precursors is often difficult, hindering the interpretation of comet nucleus compositions from coma abundances.

Recent technological advances in instrumentation have made the direct detection of parent volatiles in the coma feasible using primarily IR and radio spectroscopic techniques. It is now possible to obtain highly detailed compositional information on a large sample of comets from Earth-based observatories, and studies at radio wavelengths have resulted in the discovery of many new species with high sensitivity.[12] Although less sensitive to some minor gas species than visible or radio spectroscopy, studies at IR wavelengths can provide important information that is difficult or impossible to obtain using other methods. Direct detection of H_2O is most easily accomplished at IR wavelengths.[13] H_2O is the most abundant volatile in comets and the standard to which all other volatile abundances are compared. Remote sensing of nonpolar molecules such as CH_4, C_2H_2, and C_2H_6 is important in characterizing comet chemistry and can only be done using IR spectroscopy.[14,15]

Because observations from Earth-based observatories are only possible in some wavelength regions owing to attenuation by the terrestrial atmosphere, space-based remote sensing is needed to fill in the spectral gaps. Space-based platforms have been very successful in acquiring cometary spectra at UV (e.g., Far Ultraviolet Spectroscopic Explorer [FUSE], Hubble Space Telescope [HST]), IR (e.g., Infrared Space Observatory [ISO], Spitzer), and radio wavelengths (e.g., Submillimeter Wave Astronomy Satellite [SWAS], Odin). However, while space-based telescopes can sample spectral regions that are inaccessible from the ground, they have limited lifetimes and Sun-avoidance constraints that limit the sample size of observable comets and make many targets inaccessible when they are brightest. In addition, the spectrometer technology employed by space-based platforms generally runs behind that which is used in state-of-the-art ground-based facilities.

With the advent of advanced instruments featuring large-format detector arrays and echelle gratings,[16] ground-based IR studies can now be done with greater sensitivity, higher spectral resolution, and greater spectral coverage. In 1992, the Cryogenic Echelle Spectrometer (CSHELL) was commissioned at NASA's Infrared Telescope Facility (IRTF), a 3-m telescope at the summit of Mauna Kea in Hawaii.[17] The spectral resolution of CSHELL was much higher ($\lambda/\Delta\lambda \approx 2.5 \times 10^4$ with a 1-arcsec-wide slit) than contemporary ground-based IR instruments, providing the capability to resolve the highly diagnostic rotational-vibrational lines of molecular species. For example, Fig. 3 shows CSHELL spectra of comet C/1996 B2 Hyakutake. On the left are fully processed 2-D spatial-spectral image frames from three grating settings. The spectral and spatial dimensions are along rows and columns, respectively. Emission lines due to rotational-vibrational molecular transitions are seen superimposed above the comet continuum caused by thermal emission from dust. Regions of attenuated comet continuum are positions of terrestrial atmospheric extinction. The right side of Fig. 3 shows the corresponding extracted comet spectra (blue traces) with best-fit atmospheric/comet continuum models (dashed red traces), with cometary molecular emissions seen above the continuum and assigned.

CSHELL also provides the high spatial resolution and coverage essential for studying the manner in which volatiles are released from the nucleus. For example, Fig. 4 shows a spectrum of comet C/1995 O1 Hale-Bopp. The top frame shows a fully processed 2-D spatial-spectral image frame, this time with the spectral dimension along columns and the spatial dimension
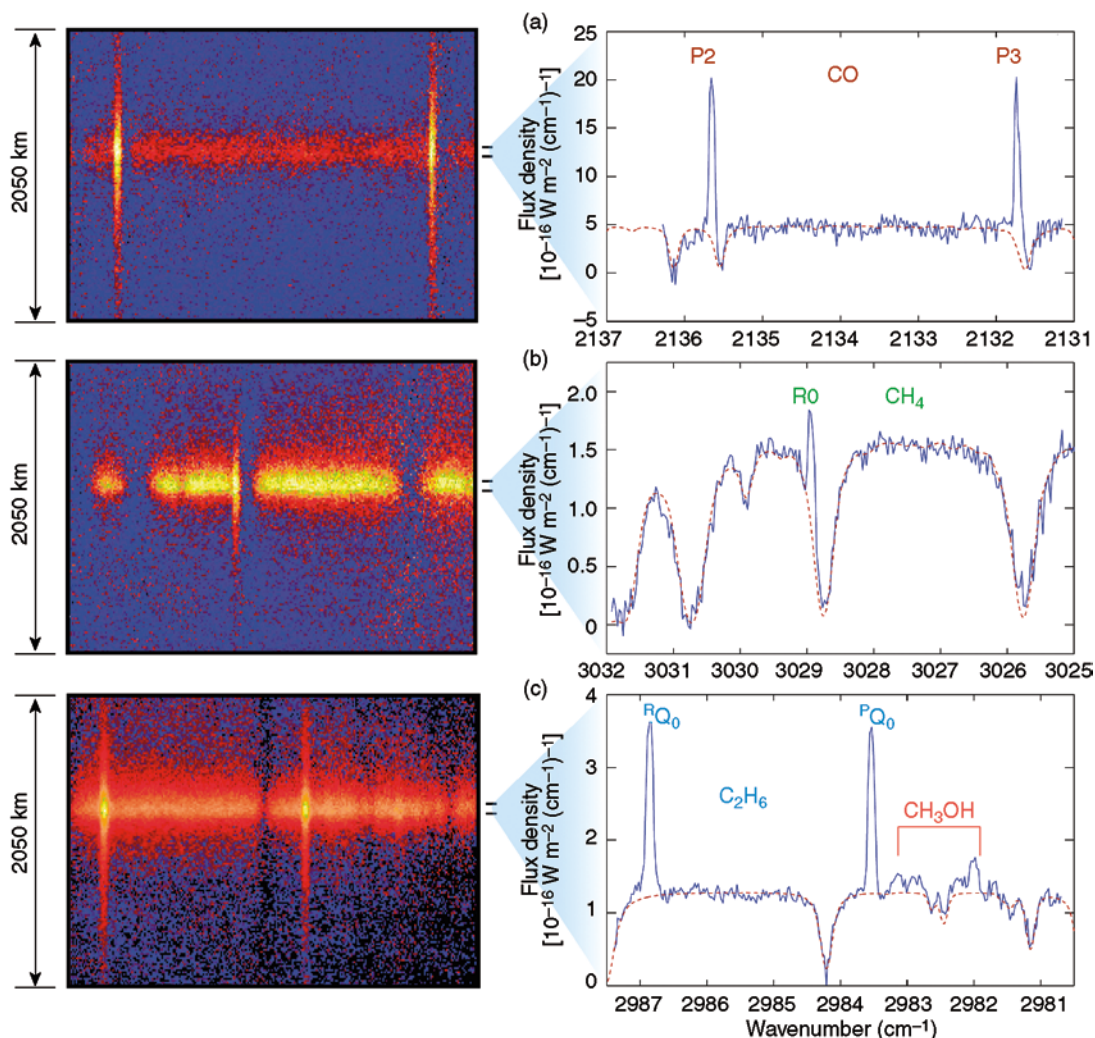
Figure 3. Spectra of comet C/1996 B2 Hyakutake (UT 24 March 1996) obtained with CSHELL at the NASA IRTF. The left panel shows fully processed 2-D spatial-spectral image frames acquired from three CSHELL grating settings with spectral resolving power $\lambda/\Delta\lambda \approx 25{,}000$. The right panel shows corresponding extracted comet spectra (blue traces) with best-fit atmospheric/comet continuum models (dashed red traces). The horizontal dashes on the right side of the corresponding figures on the left show the spatial extent of these extracts. Detected rotational-vibrational lines are for (a) carbon monoxide (CO), (b) methane (CH_4), and (c) ethane (C_2H_6) and methanol (CH_3OH). (The text discusses Fig. 3 in more detail.) (Reproduced from Ref. 15, © Elsevier, 2003.)

along rows (rotated 90° from Fig. 3). The contribution of the comet continuum has been removed to show only the spatial distribution of emissions from CO and H_2O in the comet. The bottom frame of Fig. 4 illustrates the intensity of spectral lines as a function of distance from the nucleus, clearly showing that CO and H_2O have different spatial distributions in the coma of comet Hale-Bopp. H_2O emission follows that of the dust and is consistent with release almost completely from nucleus ices. In contrast, CO shows an extended spatial emission profile consistent with a significant fraction of CO (here, about 50%) produced in the coma in addition to a nucleus ice source.[18]

CSHELL has been a workhorse in the study of other comets as well—notably 153P/Ikeya-Zhang (C/2002 C1) (spring 2002) and 2006 P1 (McNaught) (January 2007)—and has enabled the acquisition of a large database, leading to many exciting scientific results. Despite its successes, however, CSHELL provides limited spectral coverage over its 256×256 pixel InSb array (≈ 5 cm^{-1} at 5 μm and ≈ 7.5 cm^{-1} at 3.0 μm; Fig. 3), and large-scale surveys of cometary composition require many grating settings.

The commissioning of the Near-Infrared Spectrometer (NIRSPEC) at the Keck II 10-m telescope in 1999 represented the next major advance in ground-based IR
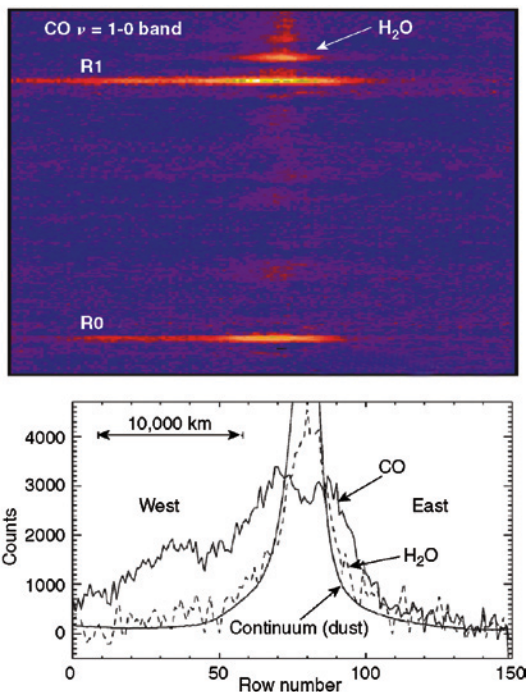
Figure 4. Spectrum of comet C/1995 O1 Hale-Bopp (UT 2 March 1997) obtained with CSHELL at the NASA IRTF. The top shows a fully processed 2-D spatial-spectral image frame from a single CSHELL setting with spectral resolving power $\lambda/\Delta\lambda \approx 25,000$. The bottom is a plot showing the intensity of spectral lines as a function of distance from the nucleus. This figure illustrates that while most (if not all) of the H_2O is released directly from ices in the nucleus, a significant fraction of CO is produced in the coma.[18] (The text discusses Fig. 4 in more detail.)

almost complete L-band survey was done at high resolution with only three NIRSPEC grating/cross-disperser settings.[21]

Measurement of the abundances of gases in the coma does not in and of itself reveal how those gases were released into the coma. Therefore, one must relate gas abundances in the coma to the composition of the nucleus. Long-slit, high-resolution IR spectroscopy can address this issue by allowing the measurement of molecular line fluxes as a function of distance from the nucleus. Line fluxes of molecules released directly from ices in the nucleus should fall off as roughly $1/\rho$, where ρ is the distance from the nucleus. This $1/\rho$ falloff is approximate because it assumes a spherically symmetric and uniform outflow of gas (sometimes not a good approximation) and that the lifetime for species in the coma is large compared to the time it takes to traverse the
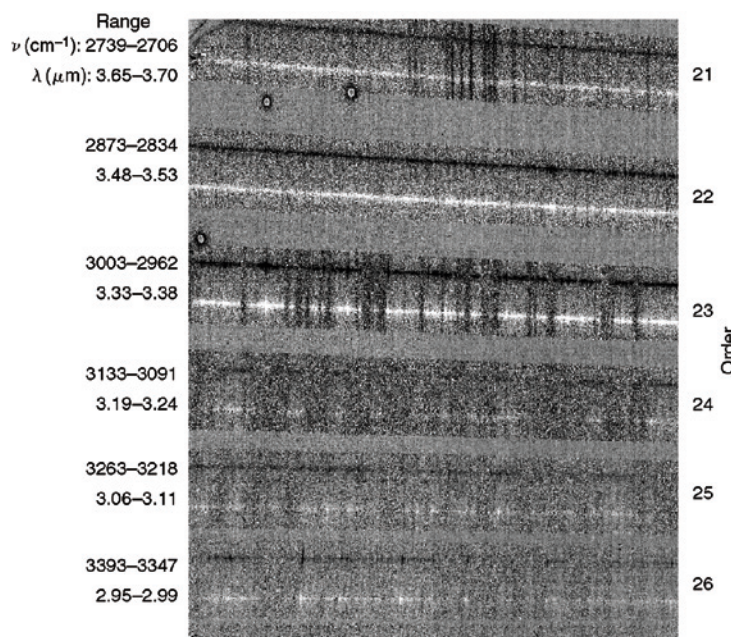

Figure 5: Spectrum of C/1999 H1 Lee acquired with NIRSPEC (UT 21 August 1999). This unprocessed spatial-spectral image frame was acquired from a single NIRSPEC echelle/cross-disperser setting ($\lambda/\Delta\lambda \approx 25,000$). To subtract the contribution from sky emission, the telescope was nodded between integrations, keeping the comet within the slit during all integrations and resulting in a positive (white) and negative (black) spectrum in each order when the difference was taken. Each echelle/cross-disperser setting encompasses multiple orders (six in this case), allowing an almost complete survey of the entire C-H stretch region (2.88–3.70 μm) with only three settings. The spectral coverage of each order (21–26) is given at the left. Comet continuum (thermal dust emission) and molecular emissions are apparent (24 min on-source). NIRSPEC thereby achieves $\approx$24 times greater spectral coverage per echelle/cross-disperser setting at these wavelengths compared with a CSHELL grating setting (see Figs. 3 and 4). This increased spectral coverage, coupled with the increased sensitivity (i.e., the 10-m Keck II telescope vs. the 3-m IRTF), permits studies of fainter comets, deeper searches for trace volatiles, and complete spectral surveys that were previously impossible (or at least impractical).[20] (Reproduced by permission of AAS.)

spectroscopy.[19] NIRSPEC combines the high spectral resolution of CSHELL with greater spectral coverage per order (by a factor of $\approx$4) along its 1024×1024 InSb detector array. NIRSPEC enjoys a further advantage in spectral coverage by employing a low-dispersion grating perpendicular to its echelle grating, allowing multiple orders (6 in the L-band [about 2.8–4.2 μm], 3 in the M-band [about 4.5–5.5 μm]) to be cross-dispersed along the array (Fig. 5). NIRSPEC thereby achieves $\approx$24 times greater spectral coverage per echelle/cross-disperser setting at L and $\approx$12 times greater coverage at M compared with a CSHELL grating setting. This increased spectral coverage, coupled with the increased sensitivity (i.e., the 10-m Keck II telescope vs. the 3-m IRTF), permits studies of fainter comets, deeper searches for trace volatiles, and complete spectral surveys that were previously impossible (or at least impractical). For example, in comet C/1999 H1 Lee, an

aperture (generally a good approximation for most species using long-slit IR spectroscopy). In contrast, molecules that formed within the coma via chemical reactions or upon dissociation of a molecule released from the nucleus will fall off more slowly with increasing distance from the nucleus (Fig. 4). Detailed analysis of the spatial distribution of species in the coma allows the differentiation and quantification of gases released directly from the nucleus (parent volatiles) and those formed in the coma (daughter fragments or distributed sources) and provides a valuable means of understanding the relationship between gases in the coma and the composition of the nucleus.[18]

Note also that molecules of different volatilities sublimate from the nucleus at different temperatures (e.g., the more volatile species sublimate at lower temperatures). Thus relative coma abundances will vary with distance from the Sun (heliocentric distance). Therefore, when assessing coma abundances in terms of nucleus compositions, measurements should be done when the comet is within about 2 AU from the Sun (and ideally closer to 1 AU), a distance at which all major species measurable at IR wavelengths should sublimate. Caution should thus be used when comparing relative coma abundances determined at different heliocentric distances within a comet or between different comets.

THE DIVERSITY OF COMET COMPOSITION

The ability to study the composition of comets via advances in IR and radio spectroscopy is barely a decade old; however, molecular abundances have been measured in enough comets that some trends are beginning to emerge. Table 1 shows the relative molecular abundances of nine species commonly measured in the coma of comets using ground-based, high-resolution IR spectroscopy. These molecules represent some of the simplest molecular species and appear to be present in most comets at abundances greater than 1 part per thousand with respect to H_2O. Establishing a formal classification of comets within this limited subset of simple molecules, however, is difficult as comets show a remarkable diversity in composition with regard to even these simple species. A similar diversity of comet composition with no definitive grouping has been observed in molecular abundances measured at radio wavelengths.[12] It is reasonable to assume that this diversity is also present in more complicated and less abundant species that cannot be

Table 1. Molecular abundances in comets.[a]

	Relative molecular abundance (% with respect to H_2O)[b]								
	H_2O	CH_3OH	HCN	NH_3	H_2CO	C_2H_2	C_2H_6	CH_4	CO
Sublimation temperature (K)	152	99	95	78	64	54	44	31	24
Comets[c]									
C/2001 A2	100	3.5	0.5		0.1	0.4	1.6	1.0	2.8
C/1995 O1	100	2.0	0.4	0.7		0.3	0.6	1.3	12.0
C/1999 T1	100	1.7	0.4				0.7	1.4	17.0
C/1996 B2	100	1.0–2.0	0.2	0.5		0.1–0.5	0.6	0.8	16.0
C/2002 T7	100	4.0			0.8				1.4
153P/I-Z	100	2.5	0.2	<0.2	0.6	0.2	0.6	0.5	4.7
C/1999 H1	100	2.0	0.2		0.7	0.2	0.7	1.4	1.5
C/2006 P1	100		0.3	2.0	0.5	0.5	0.5	0.5	2.0
9P/Tempel 1	100	1.0	0.2		0.8	0.1	0.3	<0.9	4.3
C/2000 WM1	100	1.0	0.2		0.2	0.2	0.6	0.4	1.0
2P/Encke	100	2.0	0.1			<0.2	0.3–0.7	<0.2	
73P/SW3	100	0.2	0.3	<0.2	0.1	0.03	0.1		<1.9
C/1999 S4	100	<0.2	0.08			<0.1	0.1	0.1	0.3

[a]Black = "typical," red = "depleted," green = "enhanced."
[b]Abundances are all obtained from ground-based IR measurements from Refs. 1, 19, and 22–29 except for NH_3 abundances in C/1995 O1, C/1996 B2, and 153P/Ikeya-Zhang, which were derived from measurements at radio wavelengths.[1]
[c]All comets listed are from the Oort cloud except 2P/Encke, 9P/Tempel 1, and 73P/Schwassmann-Wachmann 3, which are Jupiter-family comets thought to be from the Kuiper Belt.

measured today because of limitations in sensitivity and spectral resolution as well as the lack of relevant low-temperature laboratory data on many candidate cometary species. While samples returned by the Stardust Mission (and future missions) will undoubtedly lead to the detection of these complex cometary species in both the dust and ice, the proper interpretation of these detections requires an understanding of the diversity of composition observed in the simplest volatiles from the overall comet population.

A large-scale survey of comets at optical wavelengths suggests a dichotomy in the chemistry of comets using narrowband photometric studies.[11] About one-third (30 of 86) of the sampled comets were classified as depleted in daughter fragments C_2 and C_3 (molecules with 2 and 3 carbon atoms, respectively) relative to CN and OH, perhaps indicating differences in long-chain carbon chemistries. This study further demonstrated that significant trends appear in the carbon-chain chemistries of comets when they are broken down into classes. More than half of the Jupiter-family comets (21 of 38)—comets likely formed in the Kuiper Belt—were classified as carbon-chain depleted. In contrast, only 20% of the long-period Oort cloud comets (8 of 40) were classified as carbon-chain depleted. Halley-family comets, more highly evolved Oort cloud comets, also show a low percentage of carbon-chain depleted members (1 of 8). Although the sample size in Table 1 is small (particularly for Jupiter-family comets), similar trends are beginning to emerge; on average, Jupiter-family comets tend to be more depleted in the most volatile species than comets that originated in the Oort cloud. Are these compositional trends with class due to differences in the cometary formation region or evolutionary history (or a combination of both)?

A major goal in cometary science is to decipher the clues that measurements of comet chemistry provide on formation region and evolutionary processing history. The narrowband photometric studies hint at chemical differences possibly associated with formation region in the nebula. High-resolution IR spectroscopic studies, however, are vital to putting the photometric observations in context for two reasons. First, the parentage of C_2, C_3, and CN is not completely understood, so to interpret chemical differences rigorously, potential parent volatiles (e.g., C_2H_6, C_2H_2, and HCN) need to be measured and compared to results from narrowband photometry. These species (except HCN) can only be measured with high-resolution IR spectroscopy. Second, high-resolution IR spectroscopy can characterize more species with different volatilities. Subtle differences can be discerned when the relative abundances of organic molecules with a range of volatilities are measured, providing a more detailed picture of the role of evolutionary processing versus primordial chemistry. This is particularly important in assessing Jupiter-family comets, given

that their apparent volatile depletion relative to Oort cloud comets may be caused by thermal processing from multiple passages close to the Sun. If thermal processing from perihelion passages causes preferential loss of the most volatile species, a pattern of relative depletions of the most volatile species would be expected to be present within the comet population (especially Jupiter-family comets). However, there is no obvious evidence within the limited sample of the comet population in Table 1 that this is the case.

COMET 73P/SCHWASSMANN-WACHMANN 3: A UNIQUE OBSERVING OPPORTUNITY

The optimal method for testing the importance of thermal processing in a comet is to measure and compare cometary composition as a function of depth within the nucleus. Recall that a primary goal of the Deep Impact Mission was to study the chemistry of pristine cometary material below the outer processed layers. However, the experiment could only sample to the depths penetrated by the impactor, and long-term studies of the volatiles released by the impact were not possible because no new active vent was created (i.e., the impact-generated contribution to the coma was short-lived).

The best opportunity to date to examine the unprocessed interior of a comet using remote sensing was provided by the May 2006 apparition of 73P/Schwassmann-Wachmann 3 (Fig. 6). The splitting of this comet during a previous apparition and its continuing fragmentation during the 2006 apparition enabled the chemical sampling of material from the deep interior of the original intact nucleus through observations of the two brightest fragments of the comet, 73P-B and 73P-C. The close approach to Earth of 73P in particular allowed its chemical composition to be determined with high sensitivity.

Comet 73P/Schwassmann-Wachmann 3 is a Jupiter-family comet based on its short orbital period (5.34 years) and the low inclination of its orbit to the ecliptic (11.4°). The interior of 73P might be expected to be rich in volatile ices because it likely formed and was stored beyond Neptune in the cold Kuiper Belt; however, our spectroscopic results showed that both 73P-B and 73P-C are depleted in all measured volatile species with respect to H_2O except for HCN.[26] This is not surprising given the large percentage of carbon-chain depleted Jupiter-family comets in narrowband photometric surveys.[11] However, 73P was fragmenting and exposing fresh and presumably unprocessed material that had been deep within the original intact nucleus (Fig. 6). Furthermore, the compositions of 73P-B and 73P-C were remarkably similar, and the composition within a single fragment remained unchanged with time even as the overall activity fluctuated owing to
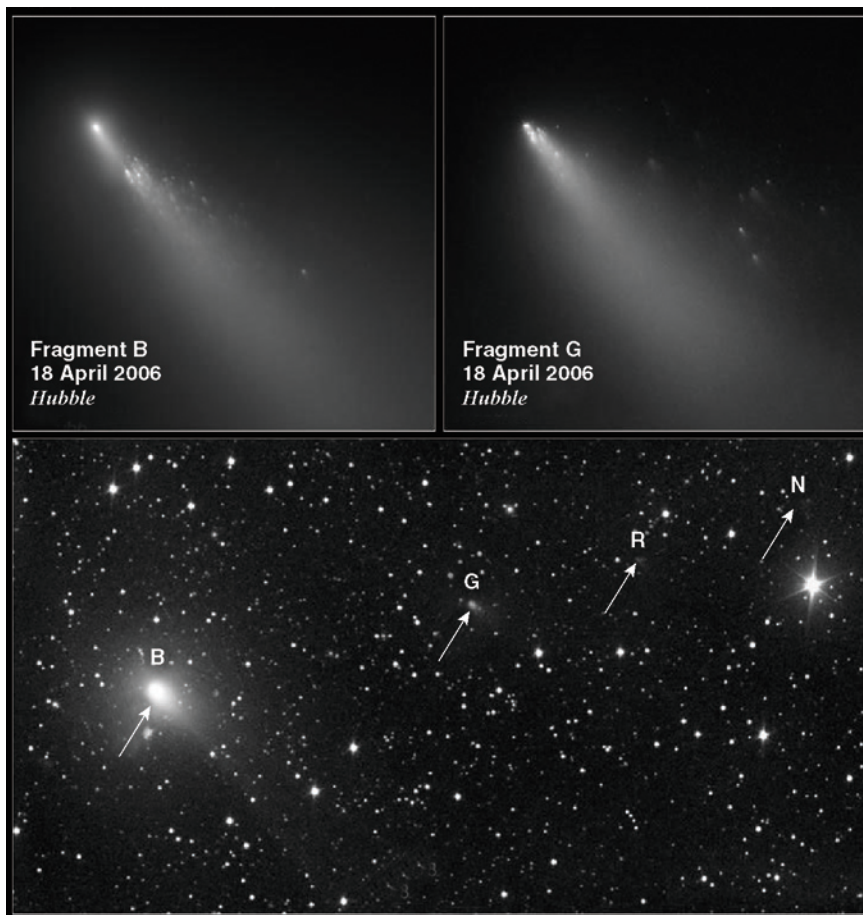
Figure 6: Images of fragmenting comet 73P/Schwassmann-Wachmann 3. (Top frames) Hubble images of fragments 73P-B and 73P-G, showing the shedding of large pieces from these fragments. (Bottom frame) Ground-based images showing several fragments of 73P. (Images courtesy of NASA, ESA, H. Weaver [APL], M. Jager, and G. Rhemann [STScI-PRC 06-18].)

turbulent mixing in the solar nebula and the migration of the giant planets during comet formation are also unclear. In addition, if the nebula lifetime was long compared to the time required for comets to accrete, the time at which a comet formed may be at least as important as formation region in determining the chemical inventory of comets. The homogeneous composition of the deep interior of 73P provides further evidence that the depleted carbon-chain chemistry measured in many Jupiter-family comets may in fact be primitive rather than evolved.

CONCLUSIONS

We are in the midst of a golden age of cometary science, when information from many areas is increasing our understanding of the relationship between cometary composition, formation region, and evolutionary history. Sample return missions are beginning to provide fundamental and detailed compositional information on individual comets using the most sensitive analytical techniques available, and future missions will continue to provide ground-breaking results. These missions

outbursts that successively exposed material to greater depth (Fig. 7).

Depletion of volatiles in 73P could indicate that its composition has evolved, even in the deep interior of its nucleus, during numerous perihelion passages; however, modeling studies suggest that thermal processing affects only the upper layers of the nucleus and not the deep interior.[2] Thermal processing alone also cannot explain why the ratio of CH_3OH to HCN, species with similar volatilities, is about a factor of 5 to 10 depleted in 73P compared to what is typically seen in comets (Table 1). Our results suggest that the original nucleus of 73P had a homogeneous composition, contrary to the view that short-period comets should show strong compositional variation with depth in the nucleus owing to thermal processing and in marked contrast to the diverse chemistry seen within the overall comet population.

These results imply that the relationship between comet formation region and composition is still not well understood. The effects on comet composition of

are crucial for understanding details about comets that are not accessible through remote sensing techniques. However, they are limited in number, while the comet population is diverse. Therefore, remote sensing remains important for obtaining less detailed but critical chemical information on a greater number of comets. Returned samples and remote sensing observations are thus both necessary and complementary: the former yields the detailed composition and structure of comets, providing ground truth to remote observations, while the latter yields the compositional context and diversity within the overall population.

Much has already been learned about comets, even from a limited dataset.

- Comets defy easy classification: their compositions are remarkably diverse, even in a small subset of simple molecules that can be routinely measured (Table 1).
- Data suggest compositional differences between long-period (Oort cloud) comets and Jupiter-family
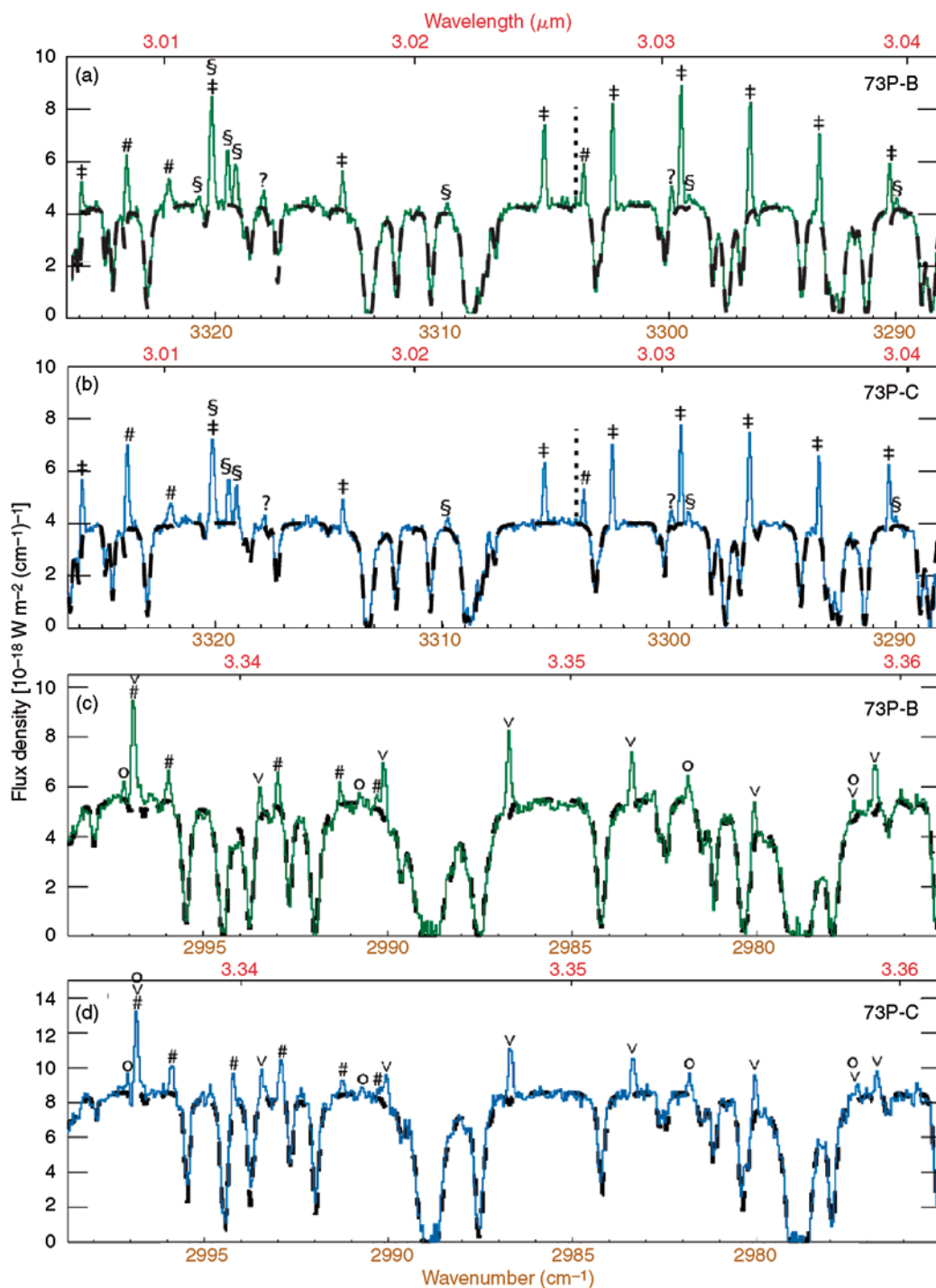
Figure 7. Selected high-resolution ($\lambda/\Delta\lambda \approx 25{,}000$) spectra of fragments B and C of comet 73P/Schwassmann-Wachmann 3 showing the detection of several species: § = H_2O, ‡ = HCN, # = OH, v = C_2H_6, o = CH_3OH, ? = unidentified. Solid green traces are the 73P-B spectra, solid blue traces are the 73P-C spectra, and dashed black traces are the best-fit synthetic atmospheric models. Molecular lines from the comet are shown as emissions in the comet spectra above the atmospheric model. (a) 73P-B on UT May 14.6 showing detections of HCN, H_2O, and OH (48 min on-source). C_2H_2 emission lines are sampled but are absent in the spectrum. The dotted vertical line near 3304 cm^{-1} denotes the expected position of the strongest unblended C_2H_2 line (v_3 R3). (b) 73P-C on UT May 15.6 covering the same spectral region as (a) (32 min. on-source). Clear detections of HCN, H_2O, and OH are seen, but as in (a), C_2H_2 emissions are absent. The dotted vertical line near 3304 cm^{-1} denotes the expected position of the C_2H_2 line. (c) 73P-B on UT May 14.6 showing detections of C_2H_6, CH_3OH, and OH (32 min. on-source). (d) 73P-C on UT May 15.6 covering the same spectral region as (c) (12 min on-source). Detections of C_2H_6, CH_3OH, and OH are indicated. Spectra of the B and C fragments are very much alike, suggesting similar chemical compositions for these fragments. This is evidence for a homogeneous volatile composition for 73P.[26]

(mostly Kuiper Belt) comets, with a greater percentage of Jupiter-family comets showing depleted carbon-chain and volatile abundances.

- Data suggest that thermal processing from multiple perihelion passages is not a major factor in observed comet chemistries; preferential depletion of the most volatile species is not seen within the comet population (Table 1).

- The recent apparition of comet 73P/Schwassmann-Wachmann 3 suggests that the depleted abundances measured in Jupiter-family comets may be primordial; however, the diversity of formation conditions and processing histories within the comet population necessitates additional observations to test whether this is generally true.

- The connection between comet composition and formative region is still not well understood. Kuiper-Belt comets formed in the coldest comet-forming regions of the early solar nebula, yet they are more commonly depleted in carbon-chain and other volatile species relative to Oort cloud comets that formed in the warmer giant planets region. This suggests that factors such as the timing of comet formation, the degree of nebular mixing, or processing differences during residence in these reservoirs rival or surpass the temperature of the formation region in determining comet chemistry.

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The Authors

Neil Dello Russo is a member of the APL Senior Professional Staff in the Space Department. Dr. Dello Russo received his B.A. in 1988 from Gettysburg College and his Ph.D. in 1994 from the University of Maryland. He worked at Goddard Space Flight Center before joining the APL staff in May 2005. His interests include acquisition, analysis, and interpretation of high- and moderate-resolution IR astronomical array data and development of low-temperature fluorescence models for interpreting the composition and excitation of detected molecules in cometary comae and other cold environments. **Harold (Hal) A. Weaver Jr.** has been pursuing space-borne, rocket-borne, air-borne, and ground-based investigations in planetary science since 1978. For his doctoral degree in physics from The Johns Hopkins University in 1982, he performed the first systematic investigation of cometary UV emissions. In 1985–1986, he and colleagues directly detected water in comets during IR observations of Comet Halley. For this work Dr. Weaver was awarded the NASA Medal for Exceptional Scientific Achievement in 1988. Since 1990, he has led many investigations of comets using the Hubble Space Telescope and the Far Ultraviolet Spectroscopic Explorer. He joined APL in May 2002 and is now serving as the Project Scientist for the New Horizons Pluto/Kuiper Belt mission. **Carey M. Lisse** is a Senior Research Scientist in the APL Space Department and is also currently a member of the Deep Impact and EPOXI Discovery Mission science teams. He received his Ph.D. in astronomy and physics from the University of Maryland in 1992 and has studied chemistry and solid state physics as well. After turning to astrophysics while building detector systems for the NASA Cosmic Background Explorer, he has studied problems in a wide-ranging number of fields, including the physical properties of primitive solar system objects; the origin and evolution of dust in comets, the IPD cloud, and the proto-solar nebula; and X-ray emission from solar system bodies and the heliosphere. **Ronald J. Vervack Jr.** received B.S. (1988) and M.S. (1989) degrees in electrical engineering from Stanford University and a Ph.D. (1997) in planetary sciences from The University of Arizona. He joined APL as a Postdoctoral Fellow in 1997 and became a member of the Senior Professional Staff in 2000. During his tenure at APL, Dr. Vervack has worked on a number of projects, including the development of a combined refractive-extinctive stellar occultation technique using MSX/UVISI data, the retrieval of atmospheric composition for Saturn and Titan from Voyager UVS occultation data, and the analysis of Venus atmospheric observations made by the Pioneer Venus Orbiter UVS. Most recently, Dr. Vervack has turned his interest to the study of cometary composition using high- and moderate-resolution spectroscopy and thermal modeling of asteroids, and he has been selected as a MESSENGER Participating Scientist to study the exosphere of Mercury. Further information about the subject of this article can be obtained from Dr. Dello Russo. His e-mail address is neil.dellorusso@jhuapl.edu.

Neil Dello Russo

Harold A. Weaver Jr.

Carey M. Lisse

Ronald J. Vervack Jr.