Parent Volatiles in Comet 9P/Tempel 1: Before and After Impact

Michael J. Mumma,1* Michael A. DiSanti,1 Karen Magee-Sauer,2 Boncho P. Bonev,1,3 Geronimo L. Villanueva,1 Hideyo Kawakita,4 Neil Dello Russo,5 Erika L. Gibb,6 Geoffrey A. Blake,7 James E. Lyke,8 Randall D. Campbell,5 Joel Aycock,8 Al Conrad,8 Grant M. Hill8

We quantified eight parent volatiles (H2O, C2H6, HCN, CO, CH3OH, H2CO, C2H2, and CH4) in the Jupiter-family comet Tempel 1 using high-dispersion infrared spectroscopy in the wavelength range 2.8 to 5.0 micrometers. The abundance ratio for ethane was significantly higher after impact, whereas those for methanol and hydrogen cyanide were unchanged. The abundance ratios in the ejecta are similar to those for most Oort cloud comets, but methanol and acetylene are lower in Tempel 1 by a factor of about 2. These results suggest that the volatile ices in Tempel 1 and in most Oort cloud comets originated in a common region of the protoplanetary disk.

Comets are the best-preserved material remaining from the earliest epoch of our planetary system, and they hold key evidence for testing their role in delivering water and prebiotic organic chemicals to the young Earth-Moon system (1–3). Today, comets reside in two principal reservoirs (the Oort cloud and Kuiper-Edgeworth belt) that have different properties. About 10 trillion comet nuclei are contained in the Oort cloud—a nearly spherical shell that spans distances ranging from 10,000 to 50,000 astronomical units (AU) from the Sun (4). The Kuiper-Edgeworth disk (KED) contains perhaps several billion comets centered on the ecliptic and orbiting at heliocentric distances ranging from ~40 to several hundred astronomical units (5, 6). The scattered KED population is thought to be the principal source of the ecliptic comets such as Tempel 1 (7). Comet nuclei can be ejected from either reservoir by various gravitational effects; once within the terrestrial planets’ region they can be activated by sunlight. If warmed sufficiently, their surface ices sublime and escaping gases can entrain small dust particles, together forming the often spectacular “tails” of dust and ionized gas seen from Earth.

Astronomers have sought to classify comets based on the composition of their native ices and dust; these should be controlled by the locations at which precometary material formed in the protoplanetary disk (8–10). A gradation in composition is expected with distance from the proto-Sun, from one dominated by interstellar chemistry at the largest distances (>40 AU) to one dominated by thermodrchemistry at the smallest comet-forming distances (~6 AU). The picture is clouded by the expected radial migration of comets within the protoplanetary disk and by the outward transport of processed grains and gases from the terrestrial planets’ region (11–13). An individual comet nucleus might contain discrete cometesimals formed in distinct regions of the disk and thus its chemical composition may well be heterogeneous. Accumulation models suggest diameters near tens of meters for such cometesimals (14).

Once a comet evolves into a short-period orbit (~200-year period), its mean lifetime against removal (complete destruction or

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Fig. 1. The development of Tempel 1 on impact night, as observed with NIRSPEC at Keck-2. (A to C) Three images taken with the SCAM, in light reflected from the polished slit plate. The black band extending left to right in each panel locates the spectrometer entrance slit. (A) The appearance of Tempel 1 just before impact. (B) The comet 27 min after impact. The edges of the spectrometer entrance slit are shown along with the cardinal directions. (C) The comet 69 min after impact. (D) Contours of the coma obtained from a median-filtered image (created from 10 SCAM frames) centered 69 min after impact. The axis of symmetry of ejection is shown along with the cardinal directions. (E) Light curves obtained from the SCAM images (black) and from the spectral continuum (3.3 μm) in individual spectra. All light curves show a rapid rise of intensity after impact. After its maximum, the peak spectral intensity (red) falls rapidly to its preimpact value by UT 7:20. The total spectral intensity (blue) decays more slowly, and the coma intensity (black) plateaus. Time blocks (KL1, KL2, and MWA) are indicated for the mean spectral extracts shown in Fig. 2.
scattering out of the solar system) is only \(\sim 500,000\) years \(15,16\). During this time, the comet nucleus may build up a surface layer of particles too large to be dragged away by the escaping gases, eventually causing sublimation to decrease markedly or even cease. Excess heating of the (inactive) surface layer could drive chemical fractionation of the layers below and might cause the released gases to differ from the pristine interior \(17\). A principal goal of Deep Impact was to test this hypothesis by excavating material from below the processed layer and measuring its chemical composition \(18\).

We measured organic volatiles and water in 9P/Tempel 1 using the high-dispersion near-infrared spectrometer (NIRSPEC) at the Keck-2 telescope on Mauna Kea, Hawaii, before, during, and after the Deep Impact event \(19,20\). Acquired spectra cover the wavelength range of 2.8 to 5.0 \(\mu\)m at a resolving power \((\lambda/\Delta\lambda \sim 24,000)\), sufficient to reveal individual spectral lines of parent volatiles.

On universal time (UT) 4 July, spectral acquisition began at 5:22 UT (shortly after sunset) and continued until 8:10 UT. For guiding, we imaged a nearby field star (using the PXL guide camera) and kept the telescope centered on the comet during the observations with the use of nonsidereal guide rates. We documented the position of the slit on the comet and recorded development of the ejecta cloud at 10-s intervals with the slit-viewing camera (SCAM) [supporting online material (SOM) text S1]. The measured stellar point-spread function (PSF) from a full set of stacked images was consistently better than 0.35 arc sec full width at half maximum (FWHM) throughout the observing of Tempel 1.

A selected sample of SCAM images is shown in Fig. 1, A to C, along with a contour map of a median-filtered image taken near UT 7:01 (Fig. 1D). The black streak appearing in Fig. 1, A, B, and C, maps the location of the entrance slit of our spectrometer (SOM text S2). The SCAM images sample light scattered from coma material at slant distances outside our slit; the slit edges and the cardinal directions on the sky are indicated in Fig. 1B. These panels show a small patch of sky \((31 \times 31\) pixels or \(5.4 \times 5.4\) arc sec) centered on Tempel 1. The total coma intensity (background subtracted) was extracted from a box \((27 \times 27\) pixels) centered on the comet, and its temporal evolution is shown in Fig. 1E (coma). The coma brightened noticeably in the first minute after impact, achieved its maximum brightness at \(\sim6:37\) UT, and maintained that brightness until our observations ceased at 8:10 UT (Fig. 1E).

We used three separate spectrometer settings (horizontal bars, Fig. 1E) (SOM text S3). The first setting (KL1, 28 min total time on source) revealed spectral lines of \(\text{H}_2\text{O}\) (four lines), \(\text{C}_2\text{H}_6\) (six Q-branches), and \(\text{CH}_3\text{OH}\) (many lines). The second setting (KL2, 24 min on source) yielded lines of \(\text{H}_2\text{O}\) (seven lines), HCN (eight lines), \(\text{CH}_3\text{OH}\) (many lines), \(\text{C}_2\text{H}_2\) (two lines, tentatively), and a tentative detection of \(\text{CH}_4\). The third setting (MWA, 14 min on source) revealed \(\text{H}_2\text{O}\) and CO.

We also extracted the peak intensity of the dust spatial profile measured along the slit and the spatially integrated intensity (Gaussian-equivalent area) implied by the spatial profile (Fig. 1E) (SOM text S4). The peak intensity samples a region close to the nucleus (e.g., a PSF of 0.35 arc sec corresponds to half width at half maximum of \(\sim113\) km at the comet), and so it represents our best information on the ejection event and its evolution with time. The peak intensity grew rapidly for the first 15 min after impact but then stabilized and thereafter decreased to values similar to the quiescent state (Fig. 1E). The spatially integrated intensity also rose rapidly toward its maximum but then fell off more slowly than the peak intensity. The rapid growth of both spectral signatures requires an increase in the effective dust cross-section and possibly in its temperature. A full treatment must

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**Fig. 2.** Detection of parent volatiles and dust in comet Tempel 1 on UT 4 July, after the impact event. We averaged over the intervals shown in Fig. 1E. The dashed line in each panel represents the cometary continuum convolved with a synthetic transmittance spectrum of the terrestrial atmosphere. (A and B) Spectra extracted from setting KL1. (A) Four spectral lines of \(\text{H}_2\text{O}\) are shown. (B) Six Q-branches of \(\text{C}_2\text{H}_6\) are detected along with features of \(\text{CH}_3\text{OH}\). (C to E) Spectra extracted from setting KL2. (C) Five spectral lines of \(\text{H}_2\text{O}\) are marked. (D) Seven \(\text{H}_2\text{O}\) spectral lines are seen in the residuals of (C) after subtraction of the cometary continuum convolved with the atmospheric transmittance. (E) Eight spectral lines of HCN are detected, along with two lines of \(\text{C}_2\text{H}_2\). Quantitative results are given in Table 1.
Table 1. The parent volatile composition of comet 9P/Tempel 1. H2O is measured in every instrument setting, and it provides the standard for abundance ratios of trace species (SOM text S8). We tabulate the effective line flux required to produce the derived column number and global production rates (SOM text S9). The temperature is the rotational temperature, determined from Boltzmann analysis of individual line intensities. If too few lines were available for independent rotational analyses, a representative value (40 K) was adopted. The reported errors in production rates (Q) and relative abundances are 1σ standard errors, which incorporate not only photon noise but also uncertainties in line-by-line evaluation of Q for the same species (SOM text S10). This approach is consistent with our previous work. In this case, 95% confidence intervals are typically 2σ or 3σ, after accounting for the limited number of lines detected. For most species, we have clear detections of more than three lines (Fig 2). The exception is CH3OH, which is based on only two sampled lines and thus has a much larger confidence interval. ph s⁻¹ molec⁻¹, photons per second per molecule.

<table>
<thead>
<tr>
<th>Species detected</th>
<th>Line flux 10⁻¹⁹ W m⁻²</th>
<th>g₅</th>
<th>Temperature K</th>
<th>Total no. 10²⁸ molecules (N)</th>
<th>Abundance (relative) (ratio of N’s)</th>
<th>Q 10⁻⁵ s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UT 3 June 2005</strong></td>
<td></td>
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<tr>
<td>KL1 6:37:29 to 8:08:37 44 min</td>
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<tr>
<td>H₂O</td>
<td>3.5 ± 0.27</td>
<td>0.0475</td>
<td>(40)</td>
<td>430 ± 33</td>
<td>100</td>
<td>1244 ± 95</td>
</tr>
<tr>
<td>CH₄</td>
<td>2.56 ± 0.50</td>
<td>20.2</td>
<td>(40)</td>
<td>0.84 ± 0.16</td>
<td>0.194 ± 0.041</td>
<td>2.42 ± 0.47</td>
</tr>
<tr>
<td>CH₃OH</td>
<td>1.38 ± 0.18</td>
<td>1.6</td>
<td>(40)</td>
<td>5.67 ± 0.73</td>
<td>1.32 ± 0.20</td>
<td>16.4 ± 2.1</td>
</tr>
<tr>
<td><strong>KL2 8:35:15 to 9:54:44 40 min</strong></td>
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<td></td>
</tr>
<tr>
<td>H₂O</td>
<td>2.90 ± 0.51</td>
<td>0.0405</td>
<td>(40)</td>
<td>409 ± 72</td>
<td>100</td>
<td>1184 ± 207</td>
</tr>
<tr>
<td>CH₃OH</td>
<td>3.18 ± 0.92</td>
<td>25.9</td>
<td>33.8</td>
<td>0.73 ± 0.21</td>
<td>0.18 ± 0.061</td>
<td>2.11 ± 0.61</td>
</tr>
<tr>
<td><strong>UT 4 July 2005</strong></td>
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<tr>
<td>Preimpact: KL1 5:22:12 to 5:52:13 16 min</td>
<td></td>
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</tr>
<tr>
<td>H₂O</td>
<td>2.79 ± 0.47</td>
<td>0.036</td>
<td>(40)</td>
<td>588 ± 99</td>
<td>100</td>
<td>1037 ± 174</td>
</tr>
<tr>
<td>CH₄</td>
<td>1.65 ± 0.70</td>
<td>8.95</td>
<td>(40)</td>
<td>1.59 ± 0.67</td>
<td>0.27 ± 0.12</td>
<td>2.8 ± 1.2</td>
</tr>
<tr>
<td>CH₃OH</td>
<td>1.16 ± 0.21</td>
<td>1.60</td>
<td>(40)</td>
<td>6.28 ± 1.13</td>
<td>1.07 ± 0.26</td>
<td>11.1 ± 2.0</td>
</tr>
<tr>
<td>H₂O (ord 26)*</td>
<td>4.92 ± 0.69</td>
<td>0.036</td>
<td>(40)</td>
<td>1042 ± 145*</td>
<td>100°</td>
<td>1835 ± 256</td>
</tr>
<tr>
<td>H₂O (ord 27)*</td>
<td>22.8 ± 0.64</td>
<td>0.17</td>
<td>38.3</td>
<td>984 ± 28*</td>
<td>100°</td>
<td>1734 ± 49</td>
</tr>
<tr>
<td>CH₄</td>
<td>8.16 ± 0.57</td>
<td>20.2</td>
<td>(40)</td>
<td>3.48 ± 0.24</td>
<td>0.353 ± 0.027*</td>
<td>6.13 ± 0.43</td>
</tr>
<tr>
<td>CH₃OH</td>
<td>1.80 ± 0.30</td>
<td>1.60</td>
<td>(40)</td>
<td>9.73 ± 1.64</td>
<td>0.99 ± 0.17</td>
<td>17.2 ± 2.9</td>
</tr>
<tr>
<td>Postimpact: KL2 6:43:16 to 7:24:49 24 min</td>
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</tr>
<tr>
<td>H₂O</td>
<td>9.04 ± 1.02</td>
<td>0.079</td>
<td>38.6</td>
<td>859 ± 97</td>
<td>100°</td>
<td>1703 ± 192</td>
</tr>
<tr>
<td>HCN</td>
<td>6.54 ± 0.66</td>
<td>28.1</td>
<td>37.3</td>
<td>1.81 ± 0.18</td>
<td>0.21 ± 0.032</td>
<td>3.61 ± 0.37</td>
</tr>
<tr>
<td>CH₃H₂</td>
<td>0.57 ± 0.17</td>
<td>4.1</td>
<td>(40)</td>
<td>1.08 ± 0.32</td>
<td>0.13 ± 0.04</td>
<td>2.06 ± 0.61</td>
</tr>
<tr>
<td>CH₃</td>
<td>5.45 ± 2.96</td>
<td>9.97</td>
<td>(40)</td>
<td>4.64 ± 2.52</td>
<td>0.54 ± 0.30</td>
<td>9.22 ± 0.5</td>
</tr>
<tr>
<td>H₂CO</td>
<td>2.32 ± 0.41</td>
<td>2.98</td>
<td>43.4</td>
<td>7.24 ± 1.28</td>
<td>0.84 ± 0.18</td>
<td>15.3 ± 2.7</td>
</tr>
<tr>
<td>Postimpact: H₂CO 7:38:30 to 8:10:23 14 min</td>
<td></td>
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</tr>
<tr>
<td>H₂O</td>
<td>6.14 ± 1.17</td>
<td>0.062</td>
<td>(40)</td>
<td>1192 ± 227</td>
<td>100°</td>
<td>2100 ± 400</td>
</tr>
<tr>
<td>CO</td>
<td>59.1 ± 20.7</td>
<td>13.7</td>
<td>(40)</td>
<td>51.7 ± 18.1</td>
<td>4.3 ± 1.7</td>
<td>91.3 ± 32</td>
</tr>
<tr>
<td><strong>UT 5 July 2005: MWA 5:55:20 to 7:06:40 32 min</strong></td>
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</tr>
<tr>
<td>H₂O</td>
<td>5.85 ± 1.17</td>
<td>0.062</td>
<td>(40)</td>
<td>1135 ± 227</td>
<td>100°</td>
<td>2000 ± 400</td>
</tr>
<tr>
<td>CO</td>
<td>45.4 ± 8.4</td>
<td>11.10</td>
<td>(40)</td>
<td>49.0 ± 9.1</td>
<td>4.3 ± 1.2</td>
<td>86.5 ± 16</td>
</tr>
</tbody>
</table>

*H₂O lines appeared in two spectral orders (ord 26 and ord 27) of KL1; the values retrieved for each order are given. We used the weighted mean column number (986 × 10²⁸ ± 27 × 10²⁸) when comparing abundance ratios for this setting.

consider dissolution of dust clusters as their icy "glue" sublimates, heating of dust grains as they are warmed by sunlight, reduction in optical depth as the ejecta cloud expands, and similar effects, which are beyond the scope of this Report.

The rapid fall off in peak intensity and the slower fall off in the spatially integrated spectral intensity likely represent continued expansion of the dust cloud along with cessation of ejection. The time required for material to traverse the radius of our pencil beam (~140 km) is about 5 min if the expansion velocity is 500 m/s. The integrated intensity samples dust over a larger spatial region (up to ~550 km projected distance), and so it falls more slowly as expansion continues. The SCAM images sample material over the largest spatial region (up to ~1600 km projected distance), and so they show the slowest temporal response. Inspection of the three light curves reveals this effect directly (Fig. 1E) (SOM text S4). Gas densities in the inner coma likely never reached spatial profiles representative of steady-source conditions. Mean spectra were formed for intervals after impact when the intensities were most stable (horizontal bars, Fig. 1E), and examples of time-averaged flux-calibrated spectra for Tempel 1 are shown in Fig. 2 (SOM text S5). The spectral extracts (Fig. 2) are taken from a pencil beam centered on the comet nucleus (3 × 9 pixels, subtending 280 × 1109 km and centered on the comet), and they measure the column of material distributed along the line of sight. The water column numbers extracted from these postimpact mean spectra are in agreement (within their confidence limits), and they are larger than the preimpact column number for H₂O by about a factor of 2 (Table 1). Measurements of H₂O and trace species were simultaneous in each instrument setting, eliminating many sources of systematic error and enabling a meaningful comparison of their abundance ratios based on column numbers.

Intensities were measured for individual spectral lines of H₂O, HCN, and H₂CO in the mean spectra (averaged over the sampling intervals mentioned above) and rotational temperatures were obtained independently for each species with the use of a Boltzmann analysis. The measured rotational temperatures cluster near 40 K (Table 1); where a rotational temperature could not be obtained, 40 K was assumed for other parent species reported here. We calculated the total number of molecules for each species in the column (3 × 9 pixels) using the measured (or adopted) rotational temperature.

We derived effective global production rates from nucleus-centered flux measurements (3 × 9 pixels) by adopting a standard coma model (a spherically symmetric coma with uniform outflow and steady production over the lifetime of the parent volatile) and applying standard analytical procedures (SOM text S6) (Table 1). These conditions are likely valid for the quiescent production on 3 June and 4 July (before impact) and the production rates for those times are valid (Table 1). However, the impulsive impact event is far from steady, and it likely varies for some time after ejection as icy grains sublimate, for example.
Table 2. The organic volatile composition of Tempel 1 and other comets. Citations to original source papers on Oort cloud comets appear in (10), NMS, neutral mass spectrometer.

<table>
<thead>
<tr>
<th>H$_2$O = 100</th>
<th>C$_2$H$_6$</th>
<th>HCN</th>
<th>CH$_3$OH</th>
<th>CO (native only)</th>
<th>CH$_4$</th>
<th>C$_2$H$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9P/Tempe 1</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>A. Preimpact (3 June)</td>
<td>0.194 ± 0.041</td>
<td>0.18 ± 0.06</td>
<td>1.32 ± 0.20</td>
<td>4.3 ± 1.2</td>
<td>0.54 ± 0.30</td>
<td>0.13 ± 0.04</td>
</tr>
<tr>
<td>B. Postimpact (total)</td>
<td>0.353 ± 0.027</td>
<td>0.21 ± 0.032</td>
<td>0.99 ± 0.17</td>
<td></td>
<td></td>
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<tr>
<td>C. Ejecta</td>
<td>0.59 ± 0.18</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Oort cloud comets</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>153P/ikeya-Zhang</td>
<td>0.62 ± 0.13</td>
<td>0.18 ± 0.05</td>
<td>2.5 ± 0.5</td>
<td>4.7 ± 0.8</td>
<td>0.51 ± 0.06</td>
<td>0.18 ± 0.05</td>
</tr>
<tr>
<td>Lee</td>
<td>0.67 ± 0.07</td>
<td>0.29 ± 0.02</td>
<td>2.1 ± 0.5</td>
<td>1.8 ± 0.2</td>
<td>1.45 ± 0.18</td>
<td>0.27 ± 0.03</td>
</tr>
<tr>
<td>Hale-Bopp</td>
<td>0.56 ± 0.04</td>
<td>0.27 ± 0.04</td>
<td>2.1</td>
<td>12.4 ± 0.4</td>
<td>1.45 ± 0.16</td>
<td>0.31 ± 0.1</td>
</tr>
<tr>
<td>Hyakutake</td>
<td>0.62 ± 0.07</td>
<td>0.18 ± 0.04</td>
<td>1.7 ± 0.4</td>
<td>14.9 ± 1.9</td>
<td>0.79 ± 0.08</td>
<td>0.16 ± 0.08</td>
</tr>
<tr>
<td>1P/Halley (Giotto NMS)</td>
<td>~0.4</td>
<td>~0.2</td>
<td>~1.7 ± 0.4</td>
<td>~3.5</td>
<td>~&lt;1</td>
<td>~&lt;0.3</td>
</tr>
<tr>
<td>C/1999 S4</td>
<td>0.11 ± 0.02</td>
<td>0.10 ± 0.03</td>
<td>~0.15</td>
<td>0.9 ± 0.3</td>
<td>0.18 ± 0.06</td>
<td>&lt;0.12</td>
</tr>
</tbody>
</table>

After impact, the measured column number is the sum of material from the quiescent source(s) and the impulsive event. If the new source has reached steady production by 20 min after impact, we expect the effective production rate to be a fair estimate of the true value (the true rate is likely to be larger by a factor up to about 1.6, i.e., π/2) (SOM text S7). However, the rapid decrease in peak spectral intensity after UT 6:20 demonstrates that steady-state production was not achieved (red points, Fig. 1E). Therefore, these production rates should be interpreted solely as indicators of activity—the quantitative values are sensitive to model assumptions. However, the total column number measured for water during the three time intervals was the same, suggesting that transient corrections to the steady production approximation are not large.

In contrast to the global production rate, the derived total column abundance is less sensitive to model assumptions because the two key variables (line flux and rotational temperature) are taken directly from our spectral measurements. Moreover, common observational factors (such as atmospheric seeing and guiding errors) affect all species measured in a given setting in the same way, and so they cancel when the ratio of column abundances is taken (Table 1). For dates on which gas production can be assumed to be steady in time (e.g., UT 3 June), the chemistry of released material may be taken either from column number ratios or from ratios of production rates.

We extracted column abundances and quiescent production rates for H$_2$O, C$_2$H$_6$, CH$_3$OH, and HCN on UT 3 June and again (excepting HCN) on UT 4 July (before impact) (Table 1). The abundance ratios measured on UT 3 June are more accurate because the comet was brighter then and more time was available for measurement (we used 44 min on source for KL1 on 3 June versus only 16 min preimpact on 4 July).

After impact, the total column number represents the sum of two contributions: (i) material produced by steady release during the interval before impact, and (ii) the (partially filled) column of gas resulting from the ejection event (Table 1). The total column number measured for water during the three time intervals was the same, within errors. The abundance ratios (relative to water) for minor species are taken from the ratio of column numbers (Table 1). The ratio of effective global production rates is not a valid measure of composition because the two components do not fill the coma in the same way and the assumed coma model is not appropriate for the impact ejecta.

The total column of material measured after impact was enriched in ethane by a factor of 1.82 ± 0.40 relative to material released on UT 3 June (0.353 ± 0.027 versus 0.194 ± 0.041, Table 1), but methanol and hydrogen cyanide were unchanged within errors. However, we cannot be certain that the steady production seen on 3 June and 4 July (preimpact) exhibit the same chemistry. Although the heliocentric distance was virtually unchanged during this time, it is possible that chemically distinct regions were active on these two dates. This could cause chemical differences in the released material if the nucleus is heterogeneous in its composition. For this reason, we considered two possibilities for steady production on the two dates: (i) independent chemistries and (ii) a common chemistry. For the first case, we adopted the apparent column numbers derived from measured line intensities and compared them with H$_2$O (measured simultaneously) to obtain abundance ratios (A and B in Table 2). The abundance ratios before and after impact on 4 July agree within their confidence limits, however, this test is not very sensitive or revealing because the confidence limits before impact are large (Table 1) (27).

For the second case, we assumed that the composition of material released before impact on UT 4 July was the same as that on UT 3 June. We then combined the more accurate abundance ratios of 3 June with the preimpact H$_2$O column number on 4 July to estimate the column numbers for C$_2$H$_6$, CH$_3$OH, and HCN from the steady source on impact night. We assumed this steady contribution was not affected by the impact event and we subtracted it from the total column numbers measured after impact (Table 1). The net column content represents the ejecta. The ejecta is enriched in ethane by nearly a factor of 3 (3.0 ± 1.1) compared with the quiescent source on UT 3 June (A and C in Table 2). CH$_3$OH and HCN show no difference, and other species (CH$_4$, C$_2$H$_2$, CO, and CO) were measured only postimpact.

Chemical diversity among comets (and even within a given comet nucleus) is expected if chemical gradients existed in the giant planets’ region of the protoplanetary disk. It is interesting to compare abundance ratios found for Tempel 1 with those of other comets (Table 2). The hypervolatiles CO and CH$_4$ vary strongly among comets (e.g., native CO varies by a factor of ~20 among comets, whereas CH$_4$ varies by a factor of ~7), and CO and CH$_4$ in Tempel 1 fall within these ranges. By contrast, ethane is notably constant. The dominant group of Oort cloud (OC) comets (8 of 10 OC comets) shows C$_2$H$_6$H$_2$O = 0.6:100 (Table 2). The unusual OC comet C/1999 S4 was depleted in most forms of volatile carbon, including ethane, whereas only one OC comet was enriched in ethane (C/2001 A$_2$, C$_2$H$_6$H$_2$O = 1.6:100). Among comets of probable Kuiper-Edgeworth belt origin, the values for comet 2P/Encke ([0.3 to 0.4:100] and 21P/Giacobini-Zinner ([C$_2$H$_6$H$_2$O = 0.22 ± 0.13:100]) agree with the total value for Tempel 1 after impact (B in Table 2). Methanol is somewhat lower in Tempel 1, both before and after impact.

Ethane depletion on 3 June could be the signature of thermal processing of surface material leading to preferential loss of hypervolatiles. Of the four species measured both pre- and post-impact, three are high-temperature volatiles (H$_2$O, CH$_3$OH, and HCN) that likely would not be affected by thermal processing of near-surface material. Of the hypervolatiles, only C$_2$H$_6$ was measured before impact and its abundance ratio then was significantly lower than after impact. The hypervolatiles were detected (CO) or constrained (CH$_4$) postimpact at abundance ratios that are within the range of those found for OC comets in our sample, but C$_2$H$_2$ was somewhat lower (Table 1). The observed chemical difference could instead be the signature of cosmogonic heterogeneity; radial migration in
the protoplanetary disk could cause cometesi-

mals of diverse chemistry to be incorporated
within the final nucleus. The impactor targeted a
region between two circular features on the nuc-
leus surface; these could be the exposed rims of
primald cometesi-


als, and if so, the impact


ejecta might represent material from them.


If we assume independent chemis-

tries for the steady production on these dates, then we

cannot extract separate volatile abundances for the steady (preimpact) production and the


ejecta on 4 July. If we assume a common chemistry for the steady production on 3 June


and 4 July (preimpact), the abundance ratios (relative to water) for most species in the

ejecta are within the range of those found for the dominant group of OC comets. Some dif-


ferences are noted: Methanol is lower by a


factor of about 2 in Tempel 1, as is acetylene.


These chemical similarities suggest that


Tempel-1 and most OC comets originated in a


common region of the protoplanetary disk; this is


consistent with the view that the comet nuclei in


the scattered KED [the proposed source reservoir for


most ecliptic comets (7)] and OC comets both


originated in the outer giant planets’ region of


the protoplanetary disk. The depleted ether-


abundance on 3 June and its similarity to similar


values found for 2P/Encke and 21P/Giacobini-


Zinner then suggests that the surfaces of short-


period comets have been processed thermally.


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20. We requested observing time on the two nights before


impact to guard against this problem, but it was


not awarded.


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Tempel 1 data obtained on 4 July are available via the


Keck Observatory Archive (http://www2.keck.hawaii.


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REPORT


Subaru Telescope Observations of Deep Impact


S. Sugita,1,4,5* T. Ootsubo,6 T. Kadono,1,7 M. Honda,4 S. Sako,2 T. Miyata,2 I. Sakon,3 T. Yamashita,8 H. Kawakita,9 H. Fujiwara,3 T. Fujiyoshi,8 N. Takato,8 T. Fuse,8 J. Watanabe,10 R. Furusho,11 S. Hasegawa,4 T. Kasuga,10 T. Sekiguchi,10 D. Kinoshita,12 K. J. Meech,13 D. H. Wooden,14 W. H. Ip,12 M. F. A’Hearn15


The impact cratering process on a comet is controversial but holds the key for interpreting observations of the Deep Impact collision with comet 9P/Tempel 1. Mid-infrared data from the Cooled Mid-Infrared Camera and Spectrometer (COMICS) of the Subaru Telescope indicate that the large-scale dust plume ejected by the impact contained a large mass (~10^6 kilograms) of dust and formed two wings approximately ±45° from the symmetric center, both consistent with gravity as the primary control on the impact and its immediate aftermath. The dust distribution in the inner part of the plume, however, is inconsistent with a pure gravity control and implies that evaporation and expansion of volatiles accelerated dust.


We conducted mid-infrared (mid-IR) observations of comet 9P/Tempel 1 before and after its collision with NASA’s 370-kg Deep Impact (DI) probe (1). Because mid-IR light is sensitive to dust radiation but not influenced by gas emission, it is suitable for observing the dust excavated by the DI collision. Both imaging and spectroscopic measurements were performed with the Cooled Mid-Infrared Camera and Spectrometer (COMICS) mounted on the Subaru Telescope on Mauna Kea, Hawaii. This long wavelength range is not covered by the DI spacecraft’s instruments (2), and the spatial resolution achieved by the large (8.2 m) aperture of the Subaru telescope surpasses that of space telescopes. Information on the impact physics of the DI collision is crucial to putting chemical and mineralogical data obtained by other observations (3, 4) into context.


Both N-band (8- to 13-μm) spectroscopy data and spectral energy distribution (SED) data based on multiband imaging measurements on universal time (UT) 2 and 3 July 2005 show that the cometary coma was compact [only 1.3 times the point spreading function (~0.4") of the Subaru/COMICS system at the 10.5-μm band] before the DI collision. The first image of comet 9P/Tempel 1 an hour after the impact showed a large fan-shaped plume with a symmetry line at 225° position angle (PA) from the comet nucleus (Fig. 1). This direction turned out to be close to the direction of the surface normal vector of the impact point of the comet (3).