the SJF rupture proceeds to within a few kilometers of the SAF, the rupture continues northward on the SAF. Thus, a large northern SJF event may trigger SAF rupture, perhaps similar to the $M_w \approx 7.5$ 1812 event (17) or even the $M_w = 7.8$ 1857 earthquake.

Our static modeling of a San Jacinto fault event shows that such an event also causes large positive ΔCFS along the Cucamonga fault, encouraging coupled rupture of the CF and northern SJF. If the SJF ends at the CF, and $\approx 3$ m of slip is generated at the northern end of the fault, our dynamic models indicate that rupture will jump onto the CF and propagate toward the west (Fig. 3B and movie S4). Because both static and dynamic stress changes from a CF rupture are positive along the central and eastern Sierra Madre fault, an SJF event could become a cascading rupture of the full SMF-CF system. This earthquake would have a combined rupture length of about 200 km and $M_w = 7.5$ to 7.8. The faults involved are closer to the densely populated Los Angeles metropolitan region than is the SAF, so although the predominantly along-strike rupture of the SMF-CF system would tend to moderate the near-source velocity pulses associated with rupture directivity (18), ground motion and damage would possibly exceed those generated by a repeat of the 1857 earthquake. This is among the worst-case scenario earthquakes for southern California.

**References and Notes**

9. We approximate the CF, SAF, SJF, and SMF by 15 planar surfaces based on the Southern California Earthquake Center (SCEC) Community Fault Model (19). Due to great uncertainty in the termination of the SJF and CF, we consider two variations of the geometry: The SJF ends at the CF, and the SJF penetrates through the CF.
10. In the static kinematic rupture models, we prescribe the magnitude and orientation of the slip on our faults. In the dynamic rupture models, the magnitude and orientation of fault slip develop as a result of solving the elastodynamic equations with the specified friction boundary conditions on the fault surfaces.

**Doubly Ionized Carbon Observed in the Plasma Tail of Comet Kudo-Fujikawa**

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Comet C/2002 X5 (Kudo-Fujikawa) was observed near its perihelion of 0.19 astronomical unit by the Ultraviolet Coronagraph Spectrometer aboard the Solar and Heliospheric Observatory spacecraft. Images of the comet reconstructed from high-resolution spectra reveal a quasi-spherical cloud of neutral hydrogen and a variable tail of $C^+$ and $C^2+$ that disconnects from the comet and subsequently regenerates. The high abundance of $C^2+$ and $C^+$, at least 24% relative to water, cannot be explained by photodissociation of carbon monoxide and is instead attributed to the evaporation and subsequent photoionization of atomic carbon from organic refractory compounds present in the cometary dust grains. This result serves to strengthen the connection between comets and the material from which the Solar System formed.

The first evidence for the existence of the solar wind came from observations of the tails of comets, and comets continue to

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**R E P O R T S**

11. Supporting online material is available on Science Online.
20. The Center for Advanced Computing Research provided access to the Hewlett-Packard V-Class computer at the California Institute of Technology. We thank R. Stein for sharing his updated slip model for the 1857 earthquake and R. Harris, K. Kendrick, N. King, and two anonymous reviewers for critical reviews, which improved this manuscript.

Supporting Online Material

www.sciencemag.org/cgi/content/full/302/5652/1946/DC1

SOM Text

Figs. S1 and S2
Tables S1 to S3
Movies S1 to S4
References

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the spatial resolution was 21 arc sec (compared with 70 arc sec for the intermediate data sets), and the number of exposures obtained was large. The spectral resolution for all observations was 0.04 nm or better. Although Kudo-Fujikawa had an orbital velocity of nearly 100 km s\(^{-1}\) during our observations, essentially all of this motion was in the plane of the sky; hence, there was no radial velocity component to produce a Doppler shift in the spectral lines.

Water is the main constituent of cometary gas. \(H_2O\) molecules released from the nucleus are photodissociated through the reactions \(H_2O + hv \rightarrow H + OH\) and subsequently \(OH + hv \rightarrow H + O\), where \(h\) is Planck’s constant and \(v\) is photon frequency. In order to calculate the rate of production of atomic hydrogen, \(Q_H\) (atoms s\(^{-1}\)), and hence the water-production rate, \(Q_{H2O}\) (molecules s\(^{-1}\)), of Kudo-Fujikawa, we constructed a simple empirical model. This model takes \(Q_H\), a quantity that we assume varies linearly with time, along with the expansion velocity of the H away from the nucleus and generates a profile for the column density, \(N(r)\), of H in the coma as a function of cometocentric distance \(r\). The situation is complicated in comparison to previous work (5) because of the high gas production of Kudo-Fujikawa. The gas within the photodissociation zone is dense enough that collisions with \(H_2O\) molecules and OH radicals thermalize much of the atomic H. This requires us to use a model for the H that includes two velocity components, \(v_1 = 5\) km s\(^{-1}\) and \(v_2 = 20\) km s\(^{-1}\) (6). The weighting of these components is a free parameter in our model, and we find that it varies from \((w_1, w_2) = (0.2, 0.8)\) to \((w_1, w_2) = (0.3, 0.7)\) as the outgassing rate (and hence the density of the inner coma) increases. We also include an exponential decay factor in our density profiles to account for the destruction of H by photoionization, charge transfer, and collisions with electrons (7). From the column densities for the slow- and high-speed components of atomic H, we compute the optical thickness for each component as \(\tau = N(r)\sigma\), where \(\sigma\) is the scattering cross section, dependent on \(v_r\).

Radiance profiles for the H I Lyman \(\alpha\) 121.6-nm line are generated by first assuming the optically thin case for each H velocity component, for which the radiance has the form \(I_H(r) = N(r)g/(4\pi r)\) with a \(g\) factor of 0.0865 (8). We then modify \(I_H(r)\) for the case of finite optical depth (9) to compute the final model radiance profile, \(H(r)\), that is compared to the observed Ly \(\alpha\) radiance profile (Fig. 1). Our best models give \(Q_H = 1.1 \times 10^{30}\) s\(^{-1}\) at the time of the first crossing, increasing to \(5.3 \times 10^{30}\) s\(^{-1}\) by the last crossing. These numbers correspond to water outgassing rates of \(5.5 \times 10^{29}\) s\(^{-1}\) to \(2.65 \times 10^{30}\) s\(^{-1}\). The model can be modified to use the radiance of the H I Ly \(\beta\) 102.6-nm line instead, allowing us to determine \(Q_H\) for two of the intermediate crossings where Ly \(\alpha\) was not within the spectral range covered (Table 1). The increase in gas production over the 30 hours of our observing run is consistent with SOHO/Large Angle Spectroscopic Coronagraph (LASCO) light curves (10).

In addition to the Ly \(\alpha\) and Ly \(\beta\) lines, we also observe emission from C III at 97.7 nm, the C II doublet at 103.6 and 103.7 nm, and three weak O I lines at 98.9, 99.0, and 102.7 nm (Fig. 2). (C III and C II are spectroscopic notation for emission from \(C^2+\) and \(C^+\), respectively.) The C III line is the strongest of these by far. By comparing the strength of each line to that of Ly \(\beta\) and taking into account the appropriate branching ratios, oscillator strengths, and solar line intensities, we derive abundances of \(C^2+\), \(C^+\), and O with respect to H. We find that \(\frac{C^2+}{C^+} = 0.13 \pm 0.01\), a ratio consistent with photoionization alone as the source of the observed carbon ions (11). Oxygen is present in an amount consistent with the water outgassing rate, although there is a relatively large uncertainty (~40%) in the O/H abundance.

Multiple UVCS spectra can be combined to form a two-dimensional image of a bright emission line. First, the desired emission line intensity is extracted from all spectra. Each 120-s exposure is then treated as an image of the narrow slice of the comet visible through the spectrograph slit at that time. Because the comet is moving as it
crosses the slit, each successive exposure captures a new slice. On the basis of the known velocity of the comet, we position each consecutive slit image within a larger array and thereby reconstruct the full image of the comet. The velocity vector of the comet was not perpendicular to the long dimension of the slit, so the resulting images have a characteristic parallelogram look, reflecting the adjustment of the raster rows to avoid distortion. As a final step, we overlay images made from the C III 97.7-nm line onto the corresponding Ly α images. The resulting composites (Fig. 3) show a quasi-spherical cloud of neutral H. The Ly α emission is visibly brighter in the later image, reflecting the increase in water production closer to perihelion. The C III emission, however, bears no resemblance to the H distribution and indeed exhibits a different morphology in the two images.

The confinement of the C2+ and other ions to the plasma tail follows the theory of “draped” magnetic field lines at comets (12, 13). An induced magnetotail forms in which the ions are channeled into a narrow region downstream of the nucleus. Plasma tails have historically been observed in the visible-light emission of the ions CO2+ and H2O+. The C2+ emission reveals the highly foreshortened plasma tail in the ultraviolet, but the inferred structure of the tail should be independent of the ion observed. Our first image has caught a disconnection event (DE) in progress, in which a bright, separated tail drifts antisunward as a new, dimmer tail forms. DEs are probably caused by the disruption of the magnetotail when the comet crosses the heliospheric current sheet (1, 14). The DE in Kudo-Fujikawa must have occurred shortly before our first observation, and the track of the comet did indeed cross the location of the current sheet expected from source surface models (15, 16), near Carrington longitude 160°. Assuming radial solar wind flow, the wind speed can be estimated from the orientation of the tail. The newly formed tail in the first image agrees with a wind speed of 210 km s⁻¹. The comet then appears to have moved into a regime of faster wind speed. The unusual tail curvature in the second image is consistent with the comet having encountered a wind velocity falling from 500 to 180 km s⁻¹ in about 2 hours, followed by half an hour of steady, 180 km s⁻¹ flow. This anomalous velocity decrease could possibly be explained by either nonradial flow of the solar wind or a slowdown of the type expected downstream of a slow coronal mass ejection (CME). Otherwise our values for solar wind speed are accurate to ±50 km s⁻¹ and are generally consistent with speeds of small CMEs tracked by LASCO (17).

The mass of the disconnected blob of C2+ in the first image is 3.7 × 10⁷ kg. The mass of the C2+ tail in the second image is 7.8 × 10⁸ kg. Assuming that C2+ is present in the ratio C2+/C⁺ derived above, the total number of carbon ions, nC2+, is 3.4 × 10⁴⁴. Because the plasma tail was visibly disrupted in the first image, we can assume that the age of the bright plasma tail in the second image is less than Δt = 30 hours; hence, the lower limit on the production rate of the ions is Qc = nC2+/Δt = 3.1 × 10³⁴ s⁻¹. This is a large value, corresponding to 24% of the mean water outgassing rate over the interval Δt. It should be noted that nC2+ itself is probably an underestimate. We are uncertain of the detailed dynamics of the plasma tail, but when the ions within the tail accelerate to speeds greater than 50 km s⁻¹ in the antisolar direction, the cometary C III line will be shifted out of resonance with the solar emission, becoming substantially dimmed. Hence, Qc could be higher by a factor of ~2 or more than the value quoted here.

The assumed primary source of carbon in cometary atmospheres is the dissociation of CO, and the relative abundance of CO to H₂O varies from 0.4% to 20% among observed comets (18, 19). Other carbon-bearing molecules, notably CO₂, CN, and CH₃OH, are less abundant than CO. We looked for the CO C-X (0,0) band at 108.8 nm, which had previously been observed in Comet C/2001 A2 (LINEAR) (19). We place an upper limit on the CO outgassing rate of QCO/QH₂O < 10%, which rules out CO as the main source of carbon ions. Moreover, the lifetime of CO against photodissociation is ~10⁵ s at 0.2 AU.

![Fig. 3. Images of Kudo-Fujikawa reconstructed from the first and last crossings of the UVCS slit. Both images are shown on the same scale. H I Ly α emission is blue, whereas the C III is red-orange. Solar north is up, and the comet is moving south. In each panel, the white arrows indicate the direction of the Sun, whereas the red and yellow arrows show the predicted orientations of the plasma tail in the slow (400 km s⁻¹) and fast (800 km s⁻¹) solar wind regimes, respectively. The first image (left) reveals a disconnected plasma tail and a new tail growing from the nucleus. The regenerated tail has become quite bright in the second image (right), only a few hours after perihelion.](image.png)

Table 1. Selected UVCS observations and derived gas production rates Q. The UT date of January 2003 given for each observation corresponds to the time that the nucleus of the comet crossed the spectrograph slit. QH₂O = Q/H₂, where Q/H₂ is taken from our models. Note that Q for neutral O agrees well with QH₂O, time-dependent water production rates, but the limits on Q for C⁺, C2⁺, and CO relative to QH₂O rule out CO as the source of the ionized carbon. Uncertainty on the oxygen numbers is 40%.

<table>
<thead>
<tr>
<th>Observation</th>
<th>C⁺</th>
<th>C²⁺</th>
<th>O</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>UT date (day/hour)</td>
<td>Spectral range (nm)</td>
<td>QH₂O(s⁻¹)</td>
<td>Ratio Q/QH₂O</td>
<td></td>
</tr>
<tr>
<td>27/22:00</td>
<td>97.3–98.8, 120.9–122.3</td>
<td>5.5 × 10²⁹</td>
<td>91%</td>
<td></td>
</tr>
<tr>
<td>28/03:00</td>
<td>101.9–111.9</td>
<td>9.0 × 10³⁰</td>
<td>&lt;10%</td>
<td></td>
</tr>
<tr>
<td>28/18:50</td>
<td>94.2–104.2</td>
<td>1.3 × 10³⁰</td>
<td>&gt;14%</td>
<td></td>
</tr>
<tr>
<td>29/04:00</td>
<td>97.3–98.8, 120.9–122.3</td>
<td>2.7 × 10³⁰</td>
<td>&gt;18%</td>
<td></td>
</tr>
<tr>
<td>30/19:00</td>
<td>101.9–111.9</td>
<td>&gt;18%</td>
<td>21%</td>
<td></td>
</tr>
<tr>
<td>30/21:00</td>
<td>94.2–104.2</td>
<td>&gt;18%</td>
<td>2.8%</td>
<td></td>
</tr>
<tr>
<td>31/00:00</td>
<td>97.3–98.8, 120.9–122.3</td>
<td>2.7 × 10³⁰</td>
<td>110%</td>
<td></td>
</tr>
</tbody>
</table>
(20), and the molecular outflow speed is ~2 km s\(^{-1}\), implying a scale length for production of atomic carbon from CO that is greater than the width of the observed plasma tail. Clearly a source of atomic carbon independent of CO is required.

Although UVCS cannot see the dust tail, dust is the most likely source of atomic carbon. One model of comet composition describes cometary nuclei as aggregates of interstellar dust grains swept up from the outer regions of the presolar nebula (21). These grains are believed to acquire organo-refractory coatings during their prolonged exposure to the cold interstellar medium. These coatings begin to evaporate at about 500 K. A typical submicron dust grain has a predicted temperature of ~1300 K at 0.2 AU (22). Indeed, the dust tail of Kudo-Fujikawa as imaged by LASCO was faint, which might reflect depletion of the tail as a result of evaporation of the dust grains. Carbon evaporated from the dust will be photoionized relatively quickly to C\(^+\) and C\(^{2+}\).

Finally, there is a potentially interesting parallel between our observations and a phenomenon observed in the extensively studied β Pictoris (Pic) system. The often-imaged disk surrounding β Pic is believed to consist of debris from the collisional destruction of planets and planetesimals. The presence of variable absorption lines of Al III, C IV, and other ionized metallic species has been explained by a model in which kilometer-sized cometary bodies evaporate as they fall toward the star (23). We note that the optical thickness of the C III 97.7-nm line in Kudo-Fujikawa is \(\tau \approx 0.6\), sufficient to make such a line readily detectable in absorption against the strong, broad C III emission line of β Pic. If a stellar wind is present, the plasma tail will stream away from the star, giving the absorption feature a distinctive, blue-shifted profile. Indeed, a recent study of β Pic detected the C III multiplet at 117.6 nm and inferred the presence of a weak stellar wind (24). A weak, narrow absorption feature with a blueshift of ~200 km s\(^{-1}\) was marginally detected in the line profile of C III 97.7 nm. Further work on this subject should strengthen the connection between solar system comets and their extrasolar counterparts, both sharing an origin in interstellar dust.

References and Notes
7. We used solar spectra from the Thermosphere Ionosphere Mesosphere Energetics and Dynamics/Solar EUV Experiment mission (25) to obtain the ionizing flux at the time of our observations. We thus obtained a photoionization rate coefficient of 3.52 \(\times 10^{-6}\) s\(^{-1}\) for neutral H. The charge-transfer rate coefficient for H is taken to be 7.1 \(\times 10^{-6}\) s\(^{-1}\), and the electron-impact rate coefficient is 1.5 \(\times 10^{-6}\) s\(^{-1}\).
8. The \(g\) factor is the number of Ly α photons scattered per second by an H atom in the coma. We used the solar spectrum of Curdt et al. (26), scaled by a factor of 1.6 to account for solar maximum conditions, to compute the \(g\) factors for Ly α and the other spectral lines used in our analysis.
9. We treat the slow component of the H distribution as a narrow (\(\Delta v_s = 10 \text{ km s}^{-1}\)), more optically thick profile superimposed upon the broad (\(\Delta v_w = 40 \text{ km s}^{-1}\)) profile of the fast component.
11. The photoionization cross sections for C and O atoms and ions were computed with the use of the method of Verner et al. (27). With the use of the TIME/SEE spectrum, we derived rate coefficients, \(g\), for carbon ions of \([\text{C I} \Rightarrow 2.93 \times 10^{-5}\text{ s}^{-1}\), \([\text{C II} \Rightarrow 2.79 \times 10^{-6}\text{ s}^{-1}\), and \([\text{C III} \Rightarrow 4.12 \times 10^{-7}\text{ s}^{-1}\).
15. Information is available online at www.sp.ph.ic.ac.uk/~jonesg/comets_sun.
28. This work was supported primarily by NASA grant NAGS-12814. Additional support was provided by NASA grants NAGS-12865 and NAGS-11420 (UVCS/SOHO), NAGS-9599 (Planetary Atmospheres), and NAGS-12668 (Laboratory Astrophysics). This research was performed while G.H.J. held a National Research Council Research Associateship Award at NASA Jet Propulsion Laboratory. G.H.J. is a SOHO Guest Investigator. We thank P. Lamry for providing data from SOHO/LASCO.

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Fig. S1
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Direct Observations of North Pacific Ventilation: Brine Rejection in the Okhotsk Sea
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Brine rejection that accompanies ice formation in coastal polynas is responsible for ventilating several globally important water masses in the Arctic and Antarctic. However, most previous studies of this process have been indirect, based on heat budget analyses or on warm-season water column inventories. Here, we present direct measurements of brine rejection and formation of North Pacific Intermediate Water in the Okhotsk Sea from moored winter observations. A steady, nearly linear salinity increase unambiguously caused by local ice formation was observed for more than a month.

The global thermohaline circulation is primed by dense water formation in high latitudes, which leads to the gradual renewal of the deep ocean. The densest bottom water is formed in the North Atlantic and Southern Oceans. Ventilation of the intermediate layer of the ocean, however, is just as important for the global overturning circulation as is deep water formation in terms of mass, heat, and freshwater transport (J). North Pacific Intermediate Water (NPIW), the densest water formed in the North Pacific, is therefore a key water mass in the general circulation. NPIW is bounded at its top by a minimum in the vertical salinity distribution throughout the North Pacific subtropical gyre at 26.7 to 26.8 \(\sigma_T\) (2, 3) and extends down to 27.6 \(\sigma_T\) on the basis of tracers indicating renewal (4). Because NPIW isopycnals do not outcrop in the open North Pacific, ventilation by deep convection, such is in the North Atlantic, can be ruled out. Instead, this overturn is driven by wintertime brine rejection in the Sea of Okhotsk (Fig. 1), the southernmost sea with considerable seasonal ice cover in the Northern Hemisphere (~6°). Rejection of salty brine, which invariably accompanies the freezing of seawater, creates some of the densest water masses in the world ocean. As the new sea ice, which is typically 70 to 90% fresher than the seawater (7), forms, the expelled brine

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