to distorted discontinuities propagating through the comet, as were seen at comet Halley[18], but not previously detected in a tail. One of these discontinuities may be related to a solar-wind discontinuity detected by Ulysses at 00:53 UT on 1 May. The observation of such distorted discontinuities is consistent with some tail ray formation theories[19,20]. The orientations of the solar-wind field lines surrounding the tail suggest upstream pile-up, as the wind encountered the slower tail. Due to the comet's retrograde motion, the tail's orientation was almost opposite to that of the surrounding field (which followed the archimedean spiral expected from the Sun's rotation). This difference in orientations probably meant that a complex interaction region surrounded the tail.

Hyakutake was intrinsically less active than Halley (their water production rates at 0.9 AU from the Sun being 1.8×10^{29} and 5.5×10^{29} molecules s^{-1}, respectively[11,21]), but Hyakutake's small heliocentric distance on 23 April 1996 resulted in a higher production rate, making it the most productive comet encountered by a spacecraft. This event was unique; only one other unexpected encounter with a comet has been reported[22], but that comet remained unidentified. Hyakutake is the first comet to have been encountered when in the fast solar wind.

The presence of a coherent structure so far from the nucleus suggests that the plasma tails of comets may persist as discrete entities for many astronomical units. As the tail of Hyakutake persisted to Ulysses, it is likely that this structure, ultimately produced by an object only ~2.4 km across[23], survived to reach the edge of the heliosphere. ☐

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Interception of comet Hyakutake's ion tail at a distance of 500 million kilometres

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Remote sensing observations[1–5] and the direct sampling of material[6–8] from a few comets have established the characteristic composition of cometary gas. This gas is ionized by solar ultraviolet radiation and the solar wind to form 'pick-up' ions[9–11], ions in a low ionization state that retain the same compositional signatures as the original gas. The pick-up ions are carried outward by the solar wind, and they could in principle be detected far from the coma. (Sampling of pick-up ions has also been used to study interplanetary dust[12,13], Venus' tail[14] and the interstellar medium[15,16].) Here we report the serendipitous detection of cometary pick-up ions, most probably associated with the tail of

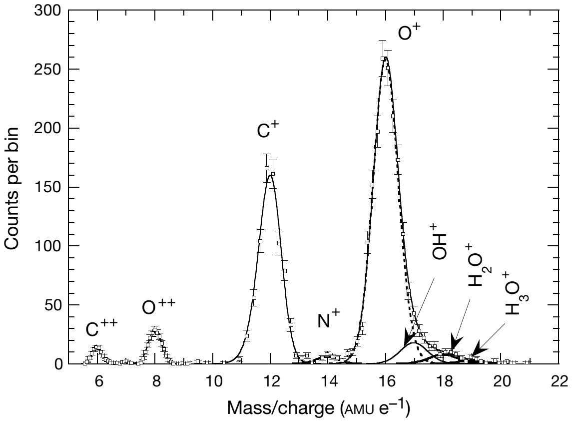

Figure 1 Mass per charge spectrum of $C^+ + O^+$ observed during a one-day period on 1 May 1996. Plotted are the average double and triple coincidence counts of ions per mass/charge (m/q) interval versus the mean m/q of each interval. Only ions with speeds above 0.8 times the simultaneously measured solar wind speed have been included. The coincidence techniques used in SWICS enable us to identify each ion by determining both its mass and mass per charge ratio and measure its speed[15,16,18]. Resolved ion species include (from left to right) C^{++}, N^{++}, O^{++}, C^+, N^+ and O^+. To obtain the abundance of each ion species we fit gaussian distributions to each of the resolved peaks as well as to the unresolved portion of the spectrum containing molecular ions with masses above 17 AMU. Counts in m/q bins above ~17 AMU e^{-1} are significantly above the dotted curve (the gaussian fit for oxygen) and correspond to singly charged molecular ions with masses of 17, 18 and 19 AMU that are not well separated from each other. The position and width (proportional to the m/q of the ion) of the gaussian distribution corresponding to each ion species is known from best fits to the resolved peaks (C^{++}, O^{++} and C^+). The amplitude of each gaussian was adjusted to minimize χ^2. The sum of the individual gaussian distributions (solid curve) is an excellent fit to the data. The abundances derived from these best fits (after efficiency corrections) are given in comet Hyakutake in Table 1. Only an upper limit could be obtained for $^{20}Ne^+$.

comet Hyakutake, at a distance of 3.4 AU from the nucleus. Previous observations have provided a wealth of physical and chemical information about a small sample of comets[6–9], but this detection suggests that remote sampling of comet compositions, and the discovery of otherwise invisible comets, may be possible.

Cometary ions have been observed during close flybys of comets, at typical distances of less than 10^7 km (refs 9–11 and 17). It was thought to be unlikely to observe such ions at much larger distances. However, on 1 May 1996 the Solar Wind Ion Composition Spectrometer (SWICS)[18] on Ulysses detected large densities of singly and doubly charged heavy ion species, well above the ubiquitous, steady, low-level pickup ion fluxes[12,13,15,16].

The composition of the ionized material we detected (Fig. 1 and comet Hyakutake in Table 1) leaves no doubt that its origin is cometary (compare to comet Halley in Table 1). Following an analysis of the magnetic field, it was concluded that field signatures seen by Ulysses on 1 May were produced by comet Hyakutake[19]. In fact, of all known comets only Hyakutake, at ~0.35 AU from the Sun, was positioned such that ionized material from its coma, embedded in the radially outflowing solar wind, would arrive 8 days later, on 1 May, at Ulysses at 3.73 AU. We were greatly surprised to find cometary material so far away from its nucleus. However, given the fortuitous alignment we conclude that the cometary ions we detected most probably came from comet Hyakutake, making it the fourth comet after Giacobini–Zinner, Halley and Grigg–Skjellerup that has been analysed with ion mass spectrometers.

The best mass spectrometer results on coma composition are those obtained from Halley by the Giotto spacecraft; we shall therefore compare the ion abundances we observed from Hyakutake with the ion composition measured in the coma of Halley. There is a remarkable similarity between the abundance patterns of all detected atomic species in the coma of Hyakutake and of Halley. The Hyakutake C^+/O^+ ratio is closer to the Halley ratio than the solar C/O ratio. The Hyakutake N^+/O^+ ratio is very close to the N^+/O^+ ratio of Halley but a factor of 5.5 lower than the solar N/O ratio. The Hyakutake Ne^+/O^+ ratio is consistent with that observed in Halley, but is very low compared to the solar Ne/O ratio. It is therefore most unlikely that the ions we observe come from an impulsive solar event spilling predominantly singly charged ions into interplanetary space. Indeed such impulsive solar events have never been observed.

The strong evolution of the composition of water group ions with distance from Halley's nucleus (see Molecules in Table 1) is well understood and agrees with model calculations. We see this pattern continuing for Hyakutake (Table 1) at more than about 10^6 km from its nucleus. Photo-dissociation of molecular H_2O and CO and the interplay between ion–molecule reactions and dissociative recombination causes fragmentation of molecules and molecular ions until the plasma contains predominantly atomic ions that have a much longer recombination lifetime than molecular ions. This evolutionary trend, both with distance from the comet and proximity to the Sun, towards a gas of mainly atomic ions is evident in the Hyakutake molecular composition data.

The differences between the Hyakutake and Halley abundances can be easily related to the factor of ~2.6 in the heliocentric distance of these two comets. Dissociation and ionization by EUV in the

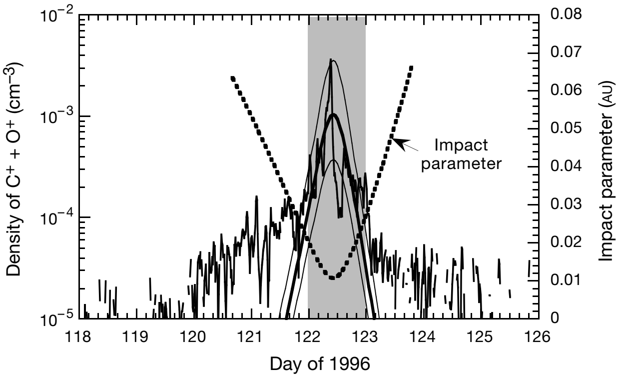

Figure 2 Density of $C^+ + O^+$ ions measured with SWICS at 3.73 AU . At the time of these observations (27 April to 5 May 1996), Ulysses was at 38° latitude in the high-speed (~750 km s^{-1}) solar wind. The dotted curve is a plot of the impact parameter *b*, defined to be the closest distance of comet Hyakutake to the line connecting the Sun and Ulysses. The 750 km s^{-1} solar wind, and the cometary ions embedded in it, take 7.92 days to travel the distance between the comet and Ulysses; thus the position of Hyakutake 7.92 days earlier is used to compute *b*. The bold curve is the predicted ion density at Ulysses based on a simple model of cometary ion production. Near the comet the density n_o of injected ions may be obtained by balancing the outward convection of cometary ions with the production rate for these ions[28]: $V_{sw} \times (dn_o/dz) = [Q/(4\pi\lambda_o r^2)] \times \exp(-r/\lambda_o)$. Here *z* is the distance along the solar wind flow line reaching Ulysses, $r^2 = z^2 + b^2$, *Q* is the gas production rate, and λ_o is the average ionization mean free path of cometary neutrals. The density of ions near the comet, n_0, is computed by integrating dn_0/dz from $-\infty$ to the radial position, *R*, of Ulysses. The predicted ion density, *n*, at Ulysses is then reduced by the radial expansion of the solar wind: $n = (r_0R)^2 n_0$, where r_0 is the radial position of Hyakutake. We obtain the best fit to the cometary ion density observed on day 122 (shaded region) using $Q = 2 \times 10^{30}\ s^{-1}$, an assumed solar wind speed near the comet (reduced by the mass loading[9]), $V_{sw} = 380$ km s^{-1} and $\lambda_o = 1.5 \times 10^6$ km (~0.01 AU). Using a combined production rate inferred for H_2O (ref. 4) and for CO (ref. 3), remote observations yield an estimate for the $C^+ + O^+$ production rate at Hyakutake's radial position (0.35 AU) of $\sim 2.4 \times 10^{30}\ s^{-1}$ (M. Combi, personal communication). The upper and lower thin curves bracketing the observed density profile around the peak are calculated in the same manner as the bold curve except that in computing these curves the value of the impact parameter *b* is changed by $\pm 0.7 \times 10^6$ km respectively, corresponding to a deviation from radial solar wind flow by ±0.08°.

Table 1 Abundances of atomic and water group ions in comets

Ratio	Comet Hyakutake* (10^6 km)	Comet Halley				Solar abundances‡
		Elements†	Molecules			
			240.000 km‖	20,000 km¶	3,000 km¶	
C^+/O^+	0.70 ± 0.06	0.6				0.49
N^+/O^+	0.024 ± 0.005#	0.025#				0.12
Ne^+/O^+	<0.005	<0.008				0.18
OH^+/O^+	0.072 ± 0.015		0.6	1	5	
H_2O^+/O^+	0.05 ± 0.01		0.2	4	40	
H_3O^+/O^+	0.015 ± 0.007		<0.02	8	200	
O^+/O^{++}	10 ± 2					
C^+/C^{++}	16 ± 3					

* Present work. For comet Hyakutake so close to the Sun, the atomic ions should correspond to the total coma abundances of C, N and O, because organic compounds, which contain significant fractions of C and N (compare ref. 22), will evaporate much faster at 0.35 AU than at 0.9 AU where comet Halley observations (columns 3–6) were made. Listed uncertainties are a combination of statistical and systematic errors.

† From ref. 23 and 24. Abundances were derived from mass-spectrometric measurements of gas and dust in Halley's coma.

‡ From ref. 27.

‖ From ref. 25.

¶ From ref. 26.

A small (compared to solar) N/O ratio is expected. The low nitrogen abundance in Halley, and probably other comets, is thought to be due to loss of N_2 or depletion of N at the time of accretion[23].

outer coma and in the tail of Hyakutake (0.35 AU) should have been basically ~7 times faster than at Halley (0.9 AU). This should result in a faster evolution towards a plasma consisting primarily of atomic ions, thus explaining the high abundance of O^+ compared to water group molecular ions in the Hyakutake plasma. H_3O^+ is produced by reactions between ions and H_2O. Its abundance falls off sharply beyond a distance from the nucleus of the comet where the H_2O density has decreased to such low values that ion–molecule reactions become ineffective. Thus, the low value of H_3O^+ observed in Hyakutake is consistent with an origin in the outer part of a coma.

As can be seen from Fig. 2, the maximum $C^+ + O^+$ density of 0.0036 cm^{-3} occurred at 9:15 on 1 May (day 122) when the Sun, comet Hyakutake and Ulysses were in closest radial alignment. At that time the shortest distance of Hyakutake to a line connecting the Sun and Ulysses 7.92 days later (the impact parameter shown as the dotted curve; see Fig. 2 legend) reached its minimum of 0.010 ± 0.006 AU or $(1.5 \pm 0.9) \times 10^6$ km. The uncertainty results from an assumed likely deviation of $\pm 0.1°$ from a strictly radial solar wind flow direction. From a fit (bold curve) to the observed density using a simple model (see Fig. 2 legend) we obtain a gas production rate of $(2 \pm 1) \times 10^{30}$ s^{-1} and an ionization mean free path of 0.01 AU for comet Hyakutake at 0.35 AU.

In the coma and tail region the mass density of cometary ions is sufficiently high to significantly deform the magnetic field configuration and decrease the solar wind speed[20]. A rough calculation using the density near the comet shows that the tail region would intersect the Sun–Ulysses line for impact parameters less than ~0.7 $\times 10^6$ km, making it quite plausible from this geometrical alignment that Ulysses detected ions from the tail region. The tail crossing is further supported by the observations shown in Fig. 3. At the time of peak density of cometary $C^+ + O^+$ ions the solar wind ion densities drop abruptly by a factor of ~5 and the proton thermal speed doubles. We interpret these solar wind signatures to be additional evidence that Ulysses traversed a portion of the plasma tail of Hyakutake, making this by far the longest comet tail ever detected.

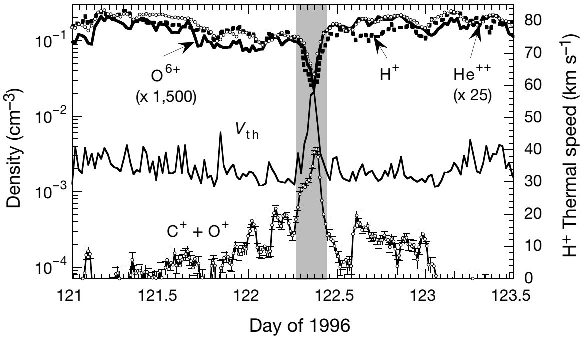

Figure 3 SWICS observations during 60 hours centred on 1 May 1996. Shown are the solar wind H^+ (squares), He^{++} (× 25; circles) and O^{6+}(×1,500; grey line) densities, proton thermal speed (V_{th}; thin line) and the $C^+ + O^+$ ion density (circles with error bars on line). The shaded region indicates the likely traversal of the distant plasma tail of Hyakutake by Ulysses, where the solar wind is significantly deformed due to the pressure of cometary ions. In this region the cometary ion density is larger than the density of solar wind minor ions (He^{++} and O^{6+}). Some of the solar wind signatures shown here were previously observed[29], but their comet-tail origin was not established until now. A gradual increase in the cometary ion density is evident days before the peak density was reached on day 122.4 and for the next few days the density gradually declined to background level (also see Fig. 2). Rapid variations in the observed $C^+ + O^+$ density are notable. This is not surprising as the source of ions at Ulysses appears point-like, and the solar wind velocity is likely to deviate from purely radial flow. The cometary ion density outside the core region is significantly above the maximum predicted density (upper thin curve in Fig. 2) using our simple model. The ions we observe outside the core region were created at larger distances from the comet in the nearly unperturbed solar wind. It is possible that these ions have subsequently undergone substantial diffusion along the magnetic field which smears the point-like cometary ion source over a wide range of impact parameters due to meandering of intertwining magnetic field lines[30]. Alternatively, more sophisticated modelling of the evolution of cometary molecules in the extended coma may account for the observed excess.

Using a dedicated instrument like SWICS that is capable of detecting atomic and molecular ions up to the mass per charge of CO^+ and S^+, retains its low background, but has a much larger sensitivity than SWICS, it will now be possible to make a comprehensive search for smaller comets. In this way, the statistics of abundances and orbits of comets can be greatly improved.

The first evidence for an invisible continuously flowing solar wind came from observations of comet tails[21]. The roles are now reversed: pick-up ion composition measurements in the solar wind are a way to detect invisible comets. ☐

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