continuous monitoring of the heliosphere with ground-based radio telescopes could substantially supplement future spacecraft observations, thus suggesting a future synergistic approach to ground- and space-based observations.

REFERENCES AND NOTES

5. The experiment was designed as a celestial mechanics experiment to measure masses, special relativity effects, and, recently, to detect large objects in the Edgeworth-Kuiper belt.
10. The data do not cover a full year because during conjunction the radio ray path passes the sun at about 11 solar radii, which is very close to the formation region of the solar wind in the ecliptic. Therefore turbulent plasma processes are dominant, and the radio signal to P10 is noisy.
13. Using 3 kHz for 1.4 solar masses, a planetary mass $m_\text{p} \approx 0.015$ Earth masses, and the planetary semimajor axis $a_m \approx 0.19$ AU, it follows from $a_{\text{syn}} = a_m / (1 + m_\text{p} / m_{\text{Earth}})$, $a_{\text{syn}} \approx 0.19$ km.
15. A possible third body with a revolution period of about 170 years was recently reported [A. Wolszczan, in Radio Pulses, D. L. Mitchell, P. W. Chodas, R. Rose, D. Kelley, M. A. Slade, M. L. Thomas, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109-8099, USA].
17. Part of this work was sponsored by the Pioneer Project, NASA Ames Research Center and was performed at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under contract with NASA. The Pioneer 10 radio Doppler data were generated with the support of JPL’s Telecommunications and Mission Operations Directorate and the DSN.

Radar observations of comet Hyakutake (C/1996 B2) made at the Goldstone Deep Space Communications Complex in California have detected echoes from the nucleus and from large grains in the inner coma. The nucleus of this bright comet was estimated to be only 2 to 3 kilometers in diameter. Models of the coma echo indicate backscatter from porous, centimeter-size grains ejected anisotropically at velocities of tens of meters per second. The radar observations suggest that a comet’s activity may be a poor indicator of its size and provide evidence that large grains constitute an important component of the mass loss from a typical active comet.

Radar Detection of the Nucleus and Coma of Comet Hyakutake (C/1996 B2)


Radar observations of comet Hyakutake (C/1996 B2) were made in March 1996 with the X-band (8510 MHz; wavelength, $\lambda = 3.3$ cm) radar on the 70-m antenna at the Goldstone facility in California. Echo detections were obtained on 24 and 25 March, when the comet was near its closest approach distance (Fig. 1). As with previous comet detections, the Hyakutake detections were made with an unmodulated continuous wave (CW) transmission (7). A 490-kW, circularly polarized wave was transmitted, and the echoes were received in the opposite sense circular (OC) and same sense circular (SC) polarizations (8). The received signal was sampled and analyzed to give calibrated (9) echo power spectra with frequency resolutions of either 19.5 Hz (low resolution) or 1.95 Hz (high resolution). The spectra were summed for each polarization to give one low-resolution and one high-resolution spectrum pair for 24 March, and one low-resolution spectrum pair for 25 March.

Both low-resolution spectra (Fig. 2, A and B) from the two successive days show a narrow spike, which is the nucleus echo, along with a broad hump skewed toward the negative side of the spike, which is the coma echo. The nucleus echo can also be seen at 210 Hz in the high-resolution spectrum (Fig. 2C). (The total bandwidth of this spectrum was too narrow to recover the full coma echo, and we have subtracted any residual coma echo left after noise baseline removal.) Integrating under the three nucleus echoes in Fig. 2 gives total radar cross...
sections $\sigma = \sigma_{\infty} + \sigma_{\infty}$ of 0.187 km$^2$, 0.192 km$^2$, and 0.178 km$^2$, respectively, with $\pm 30\%$ uncertainty (10). The nucleus polarization ratio $\mu_c = \sigma_{\infty}/\sigma_{\infty}$ ranges from 0.39 to 0.70 for the three spectral pairs and averages 0.49, indicating that Hyakutake’s decimeter-scale surface roughness is comparable with that of the rougher near-Earth asteroids (11). Because this comet is very active for its size, it is possible that the high roughness is associated with sublimation erosion or fallback of ejected debris (12).

We estimate the OC cross sections for the coma echo to be 1.25 km$^2$ and 1.42 km$^2$ from Fig. 2, A and B, respectively (with $\pm 30\%$ uncertainty). This makes the coma echo an order of magnitude stronger than the nucleus echo. The SC coma echo is weaker than the OC coma echo. This $\mu_c < 1$ behavior was also seen in the coma echoes from IAA (5) and Halley (6) and is consistent with single scattering from coma grains (8).

Attempts to make a range-resolved detection (7) of Hyakutake failed, so we were not able to measure the nucleus size directly. However, we can estimate the size of the nucleus from its radar cross section and Doppler spread. The total cross section of 0.19 km$^2$ of the Hyakutake nucleus is the second smallest of the five comets that have yielded nucleus detections (13). This implies that Hyakutake, unless it has an abnormally low radar albedo, must be a relatively small comet. Probably the most reliable estimate for the radar albedo of a comet nucleus is the 0.039 value estimated for comet IAA (14), which corresponds to a surface with the consistency of packed snow or very loose soil (5). If we assume an albedo of 0.039, we calculate a diameter of 2.5 km for Hyakutake’s nucleus (Fig. 3). This small diameter is consistent with the small Doppler bandwidth of the nucleus echo. The diameter of a nucleus with a rotation period $P$, in hours, and a rotational Doppler bandwidth $B$ (at $\lambda = 3.5$ cm) of $B$, in hertz, is given by $D = (1.0 \times 10^{-5}) BP/\sin i$, where $i$ is the angle between the line of sight and the rotation axis. We obtained an estimate of $B = 12 \pm 4$ Hz by fitting the high-resolution OC spectrum with a model nucleus echo computed from the convolution of $a \cos^{3/2} \theta$ scattering law with the $\pm 15$ Hz per hour ephemeris drift (Fig. 2C). From optical observations of coma variability and dust jet rotation, the rotation period $P$ of Hyakutake’s nucleus has been estimated to be either 6.25 hours (15) or 12.5 hours (16). Combining these B and P values gives lower limits of 0.75 or 1.5 km for the nucleus diameter for $P = 6.25$ hours and $P = 12.5$ hours, respectively (Fig. 3). Therefore, we conclude that Hyakutake is a much smaller comet than either IAA (14) or Halley (17). This is consistent with estimates and upper limits for the size of Hyakutake’s nucleus based on infrared and radio continuum observations (18). A small nucleus can also be inferred from the behavior of this comet’s orbital motion. Hyakutake is one of the few long-period comets for which the inclusion of a nongravitational outgassing acceleration model was necessary to represent properly the optical and radar Doppler observations (19). Apparently, Hyakutake’s small mass allows it to be pushed around by its active jets with relative ease.

The broadband component of the echo represents backscatter by large grains ejected from the nucleus at speeds of tens of meters per second. These grains can be anywhere within the 7000-km-diameter cylinder subtended by the radar beam at the comet, a region that includes much of the so-called “inner coma.” The coma echo is asymmetric, with most of the echo offset to the negative-Doppler side of the nucleus. This asymmetry implies an anisotropy in the direction of grain ejection. We evaluated possible grain ejection geometries and velocities using the approach of Harmon et al. (5) to the IAA coma echo. We assumed that the grains had an $a^{-3.5}$ production size distribution, where $a$ is grain radius, and that they were ejected in a 90°-wide cone at

![Fig. 1](left), Orbit geometry showing the relative positions of Earth and comet Hyakutake on 19 March 1996 (when clockwise-rotating optical dust jets were observed) and on 24 and 25 March 1996 (when the radar observations were made). Also shown are the unit vectors (arrows) for the sun and ejection cone directions corresponding to the model coma spectra plotted in Fig. 2A (24 March) and Fig. 2B (25 March).

![Fig. 2](right), Doppler spectrum pairs (OC and SC polarizations). (A) Low-resolution spectra for 24 March 1996, with model coma spectrum overplotted on the OC echo (dotted curve). (B) Low-resolution spectra for 25 March 1996, with model coma spectrum overplotted on the OC echo (dotted curve). (C) High-resolution spectra for 24 March 1996, with model nucleus spectrum overplotted on the OC echo (dotted curve). Each spectrum is an integration over the indicated UT time span. The total receive-integration time is smaller than this span, and equals 45 min for (A), 18 min for (B), and 15 min for (C). Offsets of the nucleus echo from 0 Hz are caused by errors in the Doppler prediction ephemeris used for the observations. This error also caused the echo to drift across the spectrum at a rate of $\pm 15$ Hz/hour.

![Fig. 3](Radar albedo 4a/s$^2$ of the Hyakutake nucleus as a function of nucleus diameter D for an assumed spherical nucleus (solid curve), and the estimated radar albedo of comet IAA (solid horizontal line). The corresponding error bounds (dashed lines) are given for each. Also shown are the lower limits to the nucleus diameter for rotation periods of 6.25 and 12.5 hours.)
velocities $V \approx C_a^{-1/2}$ (20). The cone direction and velocity scaling constant $C_a$ were then free parameters that could be adjusted to match the observed width and offset of the coma echo spectrum. The velocity scaling we used for the model spectra (Fig. 2, A and B) corresponds to an ejection velocity $V = 40 \text{ m/s}$ for 1-cm-radius grains. Our modeling results show that the ejection was not aimed directly at the sun, as this would have offset the coma echo toward positive Doppler shifts. There is a restricted range of directions for which the model spectra match the coma echo reasonably well (21). Examples of model spectra giving good fits are shown in Fig. 2, A and B, and their corresponding direction vectors are shown in Fig. 1. These directions are plausible if the grain ejection is determined by a thermal-phase lag in the solar activation of rotating jets. Observations of optical dust jets around 19 March (22, 23) showed a clockwise rotation, suggesting that, at that time, the nucleus was showing its south pole to Earth (23). This rotation sense is consistent with the comet-sun and ejection-cone vectors in Fig. 1. Because some antisolar directions also give good fits (21), it is possible that there may have been a contribution to the coma echo from the trailing condensation of large grains invoked by Harris et al. (24) to explain Hyakutake images obtained on 26 March. Harris et al. also argued that evaporation of large icy grains could explain the observed sphericity of the gas coma. Such icy grains, if present, could have contributed to the coma radar echo.

We estimated the grain production rate from the strength of the coma echo. We calculated the nucleus mass loss rate $M$ (in dust and large grains) from (5) using the velocity scaling from the coma spectrum fits and assuming the grains to have a density $(0.3 \text{ g/cm}^3)$ and refractive index $(n = 1.25)$ characteristic of a lightly packed snowball. The grain production size distribution was assumed to be a $a^{-3.9}$ power law between a minimum radius $a_{\text{min}}$, and maximum radius $a_{\text{max}}$ (25). The M curve (Fig. 4) shows that the largest grains must exceed 1 mm in radius, or else the grain mass loss rate far exceeds the gas production rate $M_g$, which averaged about $5 \times 10^{3} \text{ g/s}$ during this period (26). Making the maximum grain size greater than 1 cm gives $M$ values that are comparable with the gas production rate and the estimated $5 \times 10^{2} \text{ g/s}$ dust production rate (15, 26, 27). The radar M curve for $a_{\text{min}} = 1 \text{ mm}$ (Fig. 4) shows that the largest grains $(a > 1 \text{ mm})$ account for about $1 \times 10^{4} \text{ g/s}$ of the total nucleus mass loss. [This curve is also less sensitive to the assumed power law index than the $a_{\text{min}} = 1 \mu \text{m}$ case and gives a good approximation to $M$ for the case of a flatter $(a^{-3.5})$ size distribution with $a_{\text{min}} = 1 \mu \text{m}$.] Therefore, the estimated large-grain production rate inferred from the radar cross section of the coma echo is substantial, yet physically reasonable.

The calculated mass loss rates are sensitive to the assumed grain properties. Making the grains solid ice or rock gives $M$ values several times smaller than those in Fig. 4, whereas going to lighter grains increases $M$ (5). Though these uncertainties in grain density and $M$ cannot be resolved from the radar data alone, they can be reduced by comparing the radar results with millimeter-wave radio continuum measurements. In Fig. 4 we show the M required to give the continuum flux density of 220 mJy (1 Jy = $10^{-26}$ W m$^{-2}$ Hz$^{-1}$) measured at $\lambda = 1.11 \text{ mm}$ by Jewitt and Matthews (28); this was calculated with the Rayleigh-Jeans law (5) for a $0.3 \text{ g/cm}^{3}$ dirty snowball $(\eta = 1.25 - i0.01)$. Note that for $a_{\text{max}} > 1 \text{ cm}$, the radio-derived $M$ is an order of magnitude greater than the radar-derived $M$. Calculations showed that this discrepancy cannot be removed by adjusting the size distribution spectral index, nor can the radio M curve be lowered much by increasing the grain conductivity (as the large grains are already optically thick). Also, trying silicate grains with densities in the range of 0.5 to 2 g/cm$^3$ made the discrepancy worse regardless of the spectral index. It appears that the only way to reconcile the radar and radio measurements is to invoke grains that are more porous than those we have considered here. Increasing the grain porosity will raise the absorption per unit mass (or “mass opacity” $K$) as it lowers the backscatter per unit mass (29, 30), the combined effect being to bring the radar and radio curves closer to some $M$ values intermediate between the curves in Fig. 4. It is known that certain “fluffy” grains can have opacities (at $\lambda = 1 \text{ mm}$) well in excess of the $K \approx 0.4 \text{ m}^{2}/\text{kg}$ that characterizes the radio curve in Fig. 4 (29). Fluffy grains could also help to explain the relatively high velocities that were predicted by our coma spectrum model, because such grains are light and would couple more strongly to the outflowing gas (31).

REFERENCES AND NOTES___________________________
for the Halley nucleus.


20. The standard model of grain ejection by gas drag gives a terminal grain velocity $V = C_1a_{\text{m}}g$. The gravity correction $g = (1 - a_{\text{m}})^{-1/2}$ is a function of the maximum liftable grain radius $a_{\text{m}} = 18\mu J/\rho m V^3$. The gas velocity and gas mass flux at the surface, $R$ is the nucleus radius, $\rho$ and $m$ are the nucleus and grain densities, and $G$ is the gravitational constant.

21. A survey of all ejection directions shows a locus of directions giving fits with $\chi^2$ better than 1.08. These include some antisolar directions, some directions opposite the orbital angular momentum vector, and a band that crosses the comet orbit plane at an azimuth angle of ~40° to the sun direction.


25. Here $a_{\text{m}}$ is a simple size distribution cutoff introduced to show the sensitivity of $M$ to maximum grain size. We chose to use this cutoff parameter instead of the maximum liftable grain radius, $a_{\text{m}}$, because varying $a_{\text{m}}$ implies varying the grain velocity, whereas here we held the velocity constant at a fixed value determined from the coma spectrum fits. For this comet, $a_{\text{m}}$ is likely to be very large (~10 m).


31. In the standard model (20) the velocity scaling constant $C = (C_1C_2/C_3)/4 \\mu^2g/\rho/\rho/mV^3$, where $C_1$ is a drag coefficient and $C_2$, $C_3$ corrects for the change in $V$ with expansion. To get $V = 40$ m/s for homogeneous spherical grains $C_2 = 2$, $C_3 = 9/4$ of 0.3 g/cm$^3$ density and 1-cm radius requires a gas flux of $\rho = 4 \times 10^{-3}$ g/cm$^2$s for $V = 0.29$ km/s (300 K gas). This is higher than the $\rho = 5 \times 10^{-3}$ g/cm$^2$s that one expects from steady sublimation of a clean ice surface. Making the grains fluffy or fractal lowers density and $\rho$ because of the gravity correction $a_{\text{m}}$.

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**Spontaneous Formation of Macroscopic Chiral Domains in a Fluid Smectic Phase of Achiral Molecules**

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A smectic liquid-crystal phase was found to form achiral molecules with bent cores was found to have fluid layers that exhibit two spontaneous symmetry-breaking instabilities: polar molecular orientational ordering about the layer normal and molecular tilt. These instabilities combine to form a chiral layer structure with a handedness that depends on the sign of the tilt. The bulk states are either antiferroelectric-racemic, with the layer polar direction and handedness alternating in sign from layer to layer, or antiferroelectric-chiral, which is of uniform layer handedness. Both states exhibit an electric field–induced transition from antiferroelectric to ferroelectric.

Chirality has been recognized as an important feature of liquid crystals (LCs) since the time of their discovery (1). Now the influence of chirality on phase behavior and macroscopic structure is of major interest in LC science, stimulated in part by the recent discoveries of the blue phases (2) and of chiral smectic (Sm) ferroelectric (3), antiferroelectric (4), and twist grain boundary (5) phases. In these and all other known chiral LC phases, the chirality is of molecular origin, being built into the molecular structure upon synthesis, and is essentially permanent. Here we report macroscopically chiral LC phases obtained by the spontaneous chiral organization of achiral molecules. Specifically, we have found coexisting bulk fluid chiral Sm domains of opposite handedness spontaneously formed from molecules that are achiral in the isotropic phase. We provide evidence for the spontaneous formation of chiral layers in a Sm phase made from achiral molecules with bent cores [the homologous compounds 1 (6) and 2 (7) (Fig. 1)] and provide structural evidence for a symmetry-breaking transition to polar ordering in an achiral LC.

The current interest in the LC behavior of bent-core molecules has been stimulated by the synthetic work of Matsunaga and colleagues (7, 8), which includes the design and synthesis of compound 2 and its homologs (7). They identified the highest temperature Sm phase in 2 as a smectic C phase (SmC) and used x-ray layer spacing measurements of the homologous series to argue that the tails are nearly normal to the Sm layers whereas the cores are tilted. They found an 18.5 Å core thickness and, assuming a core conformation giving a 27.5 Å spacing between the alkoxyl oxygens of 2, obtained a core tilt of 48° (7).

Recently, Watanabe, Takezoe, and co-workers (6) synthesized and studied the alkyl homologs of compound 1, concluding from optical measurements that its highest temperature Sm phase had untitled cores and, from switching current measurements, that there was ferroelectric ordering of the molecular bow, with their arrows pointing in a particular direction that could be switched by an applied electric field. Study by Weissflog et al. (9) of the octyl homolog of 2 showed an antiferroelectric current response and led them to a model with an untitled core structure and antiferroelectric ordering of the molecular bow. Heppke et al. observed ferroelectric switching current dynamics in several other homologs of 1 and 2 (10).

Here we present the results of optical microscopy studies of the highest temperature Sm phase of compounds 1 and 2 in the freely suspended film (11) and “bookshelf” (12) electro-optical geometries. Our work, directed toward revealing the structure of this phase, demonstrates (i) the layer-by-layer antiferroelectric structure of the equilibrium phase, (ii) spontaneous breaking of achiral symmetry in a bulk LC (in this case into chiral Sm layers), (iii) the existence of racemic (R) and homogeneously chiral (H) stacking of these chiral layers, the racemic being the lower free-energy state, (iv) the coexistence of macroscopic, homogeneously chiral domains of opposite handedness, which maintain their handedness during electro-optic switching and are identifiable by their chiral response to applied electric field, and (v) “sergeants-and-soldiers” biasing of the global chirality by addition of chiral dopant. On the basis of these observations, we have adopted the nomenclature “SmCPa,” for this phase (13). The SmCPa phase of both compounds 1 and 2 behaved in essentially identical fashion in the film and...