not the dominant mechanism responsible for the observed energetic ions.

The shock-drift acceleration process energizes ions by magnetically driven drift along the shock electric field. Decker (*10*) showed that under appropriate conditions and particle trajectory geometries ions can be accelerated to energies that are up to two orders of magnitude higher than the "seed" population. If one assumes that the observations of several kiloelectron volt ions at Venus (*5, 6, 7*) could represent a "seed" population for the shock-drift acceleration process, the present observations of energetic ions into the 120- to 280-keV energy range can qualitatively be explained. However, a unique aspect of the geometry at Venus is that the ion energies observed have gyroradii of 1/4 to 1 R_V (H^+) or ~1 to 4 R_V (O^+). These sizes are of the order of or larger than the subsolar shock radius and imply that the subsolar shock region is not the site of the observed ion energization. In fact, the field geometry during the ion events indicates that the field line through Galileo intersected the shock a considerable distance downstream of the subsolar region.

Although shock-drift acceleration appears to be the most promising explanation of the EPD observations at this time, it is not clear whether the seed population is the solar wind or planetary pickup ions. A more detailed analysis of the data coupled with model calculations should clarify this issue.

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11. We especially acknowledge the major contributions of three EPD team members who did not live to see the results of their efforts: Wolfgang Stüdemann, James Cessna, and Eric Bubla. These three talented people were positive influences not only on the EPD team but also on all who were fortunate enough to know them. We dedicate this paper to their memory. The successful construction, test, and launch of the EPD has required the continuing efforts of many dedicated professionals. We thank those many people who had major or continuing responsibilities in the EPD effort or both. The following major contributors, exclusive of the authors of the present paper, are listed with the organizational affiliation existing at the time of their association with EPD: J. Crawford, J. Dassoulas, D. Fort, S. Gary, J. Heiss, B. J. Hook, J. Kohl, H. Malcolm, R. Moore, T. Mueller, M. Puritz, S. Purwin, N. Rothman, P. Schwartz, R. Thompson, J. Townsend, Jr., C. Wingate, and H. Wong, from The Johns Hopkins University Applied Physics Laboratory; W. Boeker, W. Klemme, H. Sommer, W. Weiss, and H. Wirbs, from the Max Planck Institute für Aeronomie; R. Dayhoff and C. Holmes, from the National Oceanic and Atmospheric Administration Space Environment Laboratory; W. Fawcett, R. Gibbs, G. McSmith, R. Parrish, J. Taylor, and J. Willett, from the Jet Propulsion Laboratory; S. Brown from Goddard Space Flight Center; and J. Burke and R. Martin, contract employees. We thank M. G. Kivelson and the Galileo magnetometer team for use of their magnetometer data in our display and analysis of EPD data. This work was supported by a National Aeronautics and Space Administration contract to The Johns Hopkins University Applied Physics Laboratory under the Department of Navy Task IAYX910X; contract N00039-89-C-0001.

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Plasma Observations at Venus with Galileo

L. A. Frank, W. R. Paterson, K. L. Ackerson, F. V. Coroniti, V. M. Vasyliunas

Plasma measurements were obtained with the Galileo spacecraft during an approximately 3.5-hour interval in the vicinity of Venus on 10 February 1990. Several crossings of the bow shock in the local dawn sector were recorded before the spacecraft passed into the solar wind upstream from this planet. Although observations of ions of the solar wind and the postshock magnetosheath plasmas were not possible owing to the presence of a sunshade for thermal protection of the instrument, solar wind densities and bulk speeds were determined from the electron velocity distributions. A magnetic field–aligned distribution of hotter electrons or "strahl" was also found in the solar wind. Ions streaming into the solar wind from the bow shock were detected. Electron heating at the bow shock, ≤20%, was notably small, with substantial density increases by factors of 2 to 3 at the day side of the shock that decrease for shock crossings further downstream from the planet. A search for pickup ions from the hot hydrogen and oxygen planetary coronas yielded an upper limit for these densities in the range of 10^{-3} ion per cubic centimeter, which is consistent with densities expected from current models of neutral gas densities.

Our current knowledge of the interaction of the solar wind with the planet Venus has been provided by a series of Mariner and Venera spacecraft and by Pioneer Venus Orbiter (*1*). The solar wind interacts directly with the planet's ionosphere and atmosphere, and thus the interaction is more similar to the situation for a comet than that of Earth, for which the solar wind is held off by our planet's magnetic field. Measurements have established that a bow shock exists at Venus and that a plasma cavity in the solar wind is formed on the dark side of the planet. Extensive observations with Pioneer Venus Orbiter provide a basis for understanding the mechanisms for the deflection of solar wind flow on the day side of the planet: at low dynamic pressures in the solar wind a magnetic barrier forms above the ionosphere, and at higher pressures ionospheric currents are driven by the induction electric field provided by the solar wind.

Electrostatic analyzers were used to provide plasma measurements over the energy per unit charge (E/Q) range of 0.8 V to 52 kV (*2*). A record of the instrument responses during the flyby of Venus is shown in the energy-time spectrograms (*3*) of Fig. 1 for two sets of sensors, E2, P2 and E6, P6. The spacecraft trajectory provided plasma measurements along the dawn flank of the bow shock and subsequently within the upstream solar wind (*4*) (see also Fig. 2). The plasma instrument was operated during the period 0318 to 0638 universal time (UT). Sensors E6 and P6 were directed most closely to the solar direction without being obstructed by the sunshade, whereas the fields of view of E2 and P2 allowed detection of electrons and positive ions, respectively, with velocity vectors directed generally toward the sun.

Crossings of the bow shock are most readily identified in the spectrogram for sensor E2 by the increases and decreases of low-energy electrons with energies ~10 to 100 eV, for example, at 0447, 0441, 0438, and 0422 UT. The regions of enhanced electron intensities occurred when the spacecraft entered the magnetosheath behind the bow shock. More accurate determinations of the times for all bow shock crossings were given by the onboard magnetometer (*5*). We list the above crossing times in reverse chronological order because in the spectrogram the electron signatures of bow shock crossings become weaker with downstream

L. A. Frank, W. R. Paterson, K. L. Ackerson, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242.
F. V. Coroniti, Departments of Physics and Astronomy, University of California, Los Angeles, CA 90024.
V. M. Vasyliunas, Max-Planck-Institut für Aeronomie, Postfach 20, W-3411 Katlenburg-Lindau, Germany.

distance along the shock, that is, decreasing UT. During the time interval 0318 to 0340 UT the electron signatures of bow shock crossings became considerably weaker. Heated positive ions in the postshock plasmas in the magnetosheath were observed with sensor P6 during the period 0318 to 0441 UT.

The electron densities and average energies for the energy range 14 to 210 eV are shown in Fig. 2. The spacecraft potential was approximately 10 V during the entire period of observations. From 0448 UT until instrument turnoff at 0638 UT the spacecraft was in the solar wind. The densities and bulk flow speeds were ~ 22 cm^{-3} and 450 km s^{-1}. These values, determined from the electron velocity distributions, are similar to those simultaneously determined from solar wind ion measurements with the plasma instrument on Pioneer Venus Orbiter (*6*). The presence of the spacecraft in the magnetosheath is evidenced by the sporadic periods of increased densities shown during 0318 to 0447 UT. The density enhancements decrease with increasing downstream (decreasing UT) distance along the bow shock.

A notable feature of the postshock magnetosheath electrons is the relatively minor heating, $\leq 20\%$ of that of the incoming solar wind temperatures. The electron plasma appears to be compressed upon passage through the shock without substantial electron heating. The velocity distribution for the solar wind electrons is shown in Fig. 3. With the exceptions of the large density increase and a minor temperature increase, the velocity distributions in the solar wind and magnetosheath are similar. Electron heating in the bow shock at Earth is not well understood (*7*). Further analysis of the present observations at Venus may provide further insight. The crossings of the bow shock at Venus occurred during a quasi-parallel geometry with the solar wind magnetic field directed generally parallel to the normal to the bow shock (*5*).

The solar wind electron distribution at energies above ~ 100 eV is magnetic field–aligned as shown in Fig. 3. Rotation of the spacecraft as the energy spectra were sampled produced the apparent rapid fluctuations shown at these energies in the spectrogram for E6 in Fig. 1. These electrons have been identified with interplanetary measurements with other spacecraft and are called the "strahl" of the electron velocity distribution (*8*). When the magnetic field geometry (*5*) was favorable, some of these electrons propagated upstream from the bow shock to the spacecraft position. For example, during the period 0600 to 0638 UT these electrons exhibited sporadic fluxes as seen in the responses of sensor E2 in Fig. 1. This region is known as the electron foreshock (*9*). At Venus the electron energies are similar to those propagating from the sun, and the electrons may be simply reflected by the magnetic barrier at the bow shock without substantial acceleration.

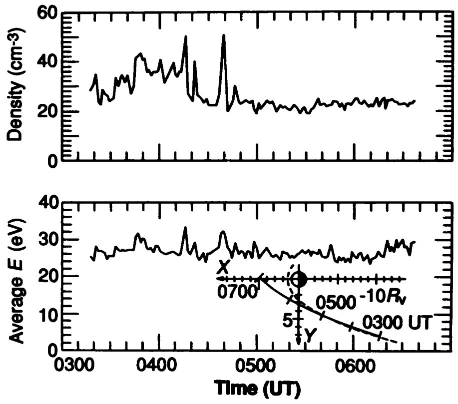

Fig. 2. Densities and average energies of electrons in the energy range 14 to 210 eV during the Venus flyby. The Galileo trajectory in the *X–Y* plane (Venus-centered solar ecliptic coordinates) and a nominal position of the bow shock are also shown.

Positive ions streaming into the solar wind from the bow shock were also detected. A similar phenomenon has been detected sunward of Earth's bow shock and is known as the ion foreshock (*10*). The two most evident cases of upstreaming ions are centered at 0504 and 0618 UT for sensors P6 and P2, respectively, in Fig. 1. Another example of upstreaming ions, much nearer to the bow shock, occurs between the two shock crossings during 0423 to 0438 UT. The upstreaming ions are in the *E/Q* range of ~ 1 to 8 kV. In order to propagate upstream from the bow shock, a proton must have a speed greater than the solar wind speed of 450 km s^{-1} or 1 keV. The spectrograms also show that the energy range is similar to that for the high-speed tail of the magnetosheath ions. These are shocked ions reflected by the magnetic barrier at the bow shock (*10*).

An example of the three-dimensional velocity distributions is shown in Fig. 4, where V_3 is directed along the magnetic field **B**. The velocity distributions are not azimuthally symmetric with respect to **B**, that is, not gyrotropic, as noted by their distribution in the V_1–V_2 plane. These velocity distributions are similar to one of the several types of upstreaming distributions observed in Earth's ion foreshock (*10*). The present observations confirm the existence of upstreaming ions reported by the plasma investigators for Pioneer Venus Orbiter (*11*). Williams *et al.* (*12*) report detection of ions with energies considerably in excess of those

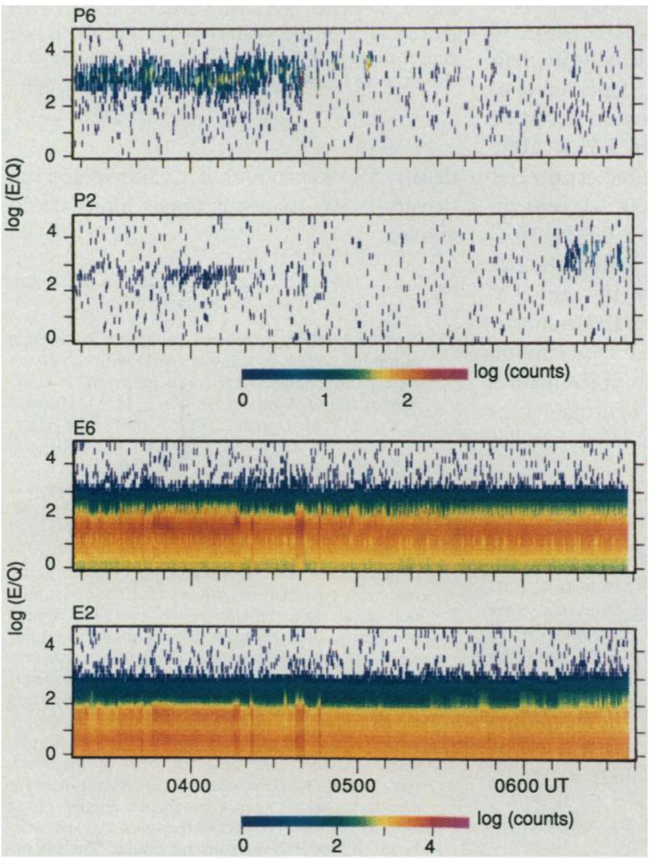

Fig. 1. Energy-time spectrograms for the positive ion sensors P2 and P6 and electron sensors E2 and E6 for the entire period of plasma observations at Venus (*E/Q* in volts).

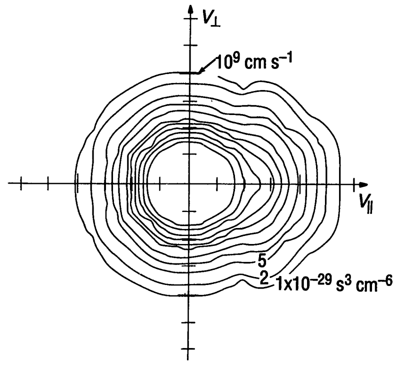

Fig. 3. Electron velocity distribution $f(\mathbf{V})$ in the solar wind from 0515:51 to 0517:14 UT. The coordinate $+V_\parallel$ is taken parallel to the interplanetary magnetic field **B**. For ease of visualization, the contours at $V_\perp < 0$ are the reflection of the contours at $V_\perp > 0$ about the $V_\parallel$-axis.

reported here. The relation, if any, of our ion observations to those at greater energies is not clear.

Venus is surrounded by extensive hot atomic hydrogen and oxygen distributions (*13*), or coronas, that interact directly with the solar wind. Hydrogen and oxygen ions are created by charge exchange with the solar wind ions and by photoionization from solar insolation. These ions are subsequently picked up by the solar wind by the $\mathbf{V}_s \times \mathbf{B}$ electric field and swept downstream with the solar wind with a velocity dependent on the orientation of the interplanetary field. Observations with Pioneer Venus Orbiter at lower altitudes have detected significant effects interpreted in terms of ion pickup near the subsolar nose of the bow shock (*14*) and the occasional presence of pickup oxygen ions further downstream (*15*). The time period we have chosen to search for such pickup ions in the interplanetary medium is 0510 to 0600 UT, a period for which no upstreaming ions are present.

In the reference frame of the solar wind a newly created ion has a gyroradius and speed parallel to **B** that depend on the direction of **B**. Thus, because the direction of **B** varies during this time, we transform all measurements into a "pickup ion reference frame" (Fig. 5) (*16*). In this reference frame V_3 is parallel to **B** and V_g is the speed of gyration of the ion. In the absence of scattering, the ion executes motion in a circle in velocity space about O′. The spacecraft rest frame is located at O. The pickup coordinates of the responses of the instrument are then individually calculated for the above interval and assigned to four zones: A (scattered pickup ions) (*17*), B (unscattered pickup ions), C (background), and D (background). The thickness of the pickup disk along V_3 is taken as $\pm 0.1\ V_g$, and zone B has a width in the V_1–V_2 plane of $0.2\ V_g$.

The results of this preliminary search are shown in Table 1 with the assumptions of hydrogen and oxygen ions, respectively. The only statistically significant response, within 3σ, occurs in zone A for singly charged oxygen ions. However, these responses are not corrected for cosmic ray background, nor is the possibility quantitatively evaluated that such responses may be due to the pickup of infalling interstellar helium (*18*). The cosmic ray background rates are difficult to evaluate because of the short duration of the observations at Venus but are typically in the range of 5×10^{-2} counts per second. Data from the mass spectrometers are not yet analyzed in detail, but their limited sampling times at Venus are not expected to further improve the following upper limits for pickup ion densities. If the responses shown in Table 1 are assumed to correspond to a constant phase space density in their respective volumes, then an upper limit to the spatial densities of pickup ions can be obtained. These densities are 2.7×10^{-3} and 8.1×10^{-3} ions per cubic centimeter for zones A and B, respectively, for oxygen, and similarly 2.0×10^{-3} and 9.9×10^{-4} ions per cubic centimeter for hydrogen. The phase space volumes are 1.8×10^{22} and 9×10^{21} cm^3 s^{-3} for zones A and B. Rudimentary calculations for the expected pickup ion densities (*19*) from the models of the neutral coronal gases yield $\sim 10^{-3}$ hydrogen ions per cubic centimeter and a much smaller

Table 1. Preliminary results from the search for pickup ions.

Zone	Samples	Counts	Counts/s (±SD)
		H^+	
A	1,483	28	9.4 (±1.8) × 10^{-2}
B	2,815	25	4.4 (±0.88) × 10^{-2}
C	3,598	48	6.7 (±0.97) × 10^{-2}
D	35,628	395	5.5 (±0.28) × 10^{-2}
All	43,524	496	5.7 (±0.26) × 10^{-2}
		O^+	
A	1,642	38	11.6 (±1.9) × 10^{-2}
B	15,314	190	6.2 (±0.45) × 10^{-2}
C	3,565	39	5.5 (±0.88) × 10^{-2}
D	23,003	229	5.0 (±0.33) × 10^{-2}
All	43,524	496	5.7 (±0.26) × 10^{-2}

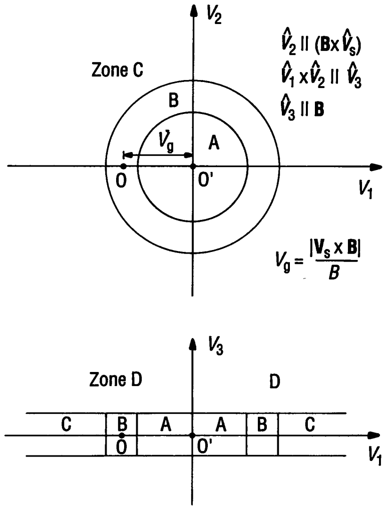

Fig. 5. Velocity coordinates used in the search for pickup ions in the vicinity of Venus. O′ is the center of gyration for pickup ions, and zone B is the expected location of the ring of pickup ions.

density for oxygen ions. This anticipated ion density is less than our upper limits noted above.

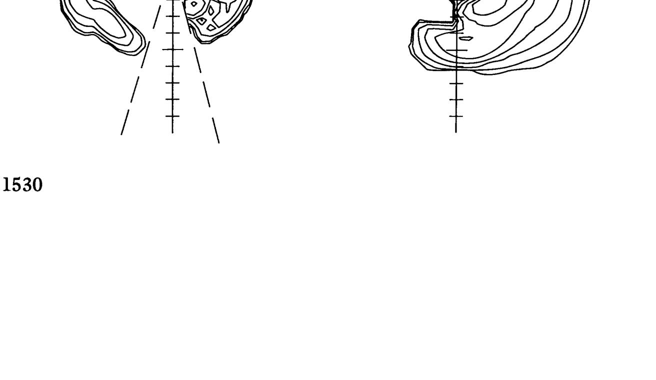

Fig. 4. Three-dimensional velocity distribution of ions upstreaming from the bow shock into the solar wind from 0618:59 to 0620:24 UT. The phase space densities are computed with the assumption that the ions are protons. The coordinate $+V_3$ is parallel to **B**. The V_2 axis is parallel to $\mathbf{B} \times \mathbf{V}_s$, where $\mathbf{V}_s$ is the antisolar direction.

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1. Two comprehensive reviews of current knowledge of the interaction of the solar wind with the planet Venus and extensive references are given by C. T. Russell and O. Vaisberg [in *Venus*, D. M. Hunten, L. Colin, T. M. Donahue, V. I. Moroz, Eds. (Univ. of Arizona Press, Tucson, 1983), pp. 873–940] and L. H. Brace *et al.* (*ibid.*, pp. 779–840).
2. A detailed description of the plasma instrument is given by L. A. Frank, K. L. Ackerson, J. A. Lee, M. R. English, and G. L. Pickett (*Space Sci. Rev.*, in press). The plasma instrumentation comprises a nested set of four spherical-segment electrostatic analyzers; two analyzers are used for the determination of the three-dimensional velocity distributions of electrons and the other two for similar measurements of positive ions. The electrostatic analyzers give the directional intensities of ions and electrons as a function of E/Q, and three miniature magnets for identifying the mass per unit charge (M/Q) are positioned at the exit apertures of the ion electrostatic analyzers. The fields of view of the seven sensors for the electrostatic analyzers for positive ions contiguously span a fan-shaped angular range of 9° to 166° with respect to the spacecraft spin axis. Fields of view for electrons are similar. The plasma

analyzer is mounted on the magnetometer boom of the spinning section of the Galileo spacecraft such that this rotation, together with multiple sensors, provides almost complete coverage of the entire solid angle for charged particle velocity vectors at the spacecraft position. Electronic sectioning divides the rotation into a number of azimuthal sectors that are preselected by ground command. The E/Q range is 0.8 V to 52 kV for positive ions and electrons. The operational mode at Venus is such that 32 E/Q passbands are sampled over this E/Q range during approximately 120° of spacecraft rotation. The spacecraft rotation period is 19.1 s. Typical energy resolution $\Delta E/E$ is 0.11. By control of the spin phase of the above sectors, 32 E/Q samples of intensities within eight azimuthal sectors for each sensor were acquired during four contiguous spacecraft rotations. The spacecraft spin axis was aligned with the direction to the sun to within a few degrees during Venus encounter. A sunshade that is used to prevent overheating of the instrument obscured the fields of view P7 and E7, which were directed most nearly to the solar direction. This sunshade prevents the detection of the solar wind ions and the bulk of the magnetosheath ion distributions.

3. Energy-time (E-t) spectrograms display the counts per accumulation period for each E/Q scan (abscissa) of the instrument. The accumulation period is 0.2 s. For the instrument operation at Venus, 32 samples at equal logarithmic intervals in E/Q were taken. The responses are logarithmically coded according to the two color bars displayed in Fig. 1, one each for the ion and electron analyzers, respectively.
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6. Values for the solar wind speeds and proton densities from the plasma instrument on Pioneer Venus Orbiter were supplied by J. D. Mihalov of the National Aeronautics and Space Administration Ames Research Center. The electron densities derived from the Galileo plasma instrument have been cross-calibrated with the Langmuir-line frequency observed with the Galileo plasma wave instrumentation (D. A. Gurnett *et al.*, *ibid.*, p. 1522).
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8. The solar wind electron distribution exhibits a cool core of electrons convecting with the solar wind ions and a suprathermal velocity distribution that includes a magnetic field–aligned "strahl" at higher energies. See, for example, W. G. Pilipp *et al.* [*J. Geophys. Res.* **92**, 1075 (1987)].
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12. D. J. Williams *et al.*, *Science* **253**, 1525 (1991).
13. On the day side of Venus the densities of atomic oxygen and hydrogen are approximately equal, ~100 atoms per cubic centimeter, at an altitude of 3000 km [G. M. Keating *et al.*, in *The Venus International Reference Ionosphere*, A. J. Kliore, V. I. Moroz, G. M. Keating, Eds., *COSPAR Advances in Space Research*, vol. 5, no. 11 (Pergamon, Oxford, 1985), pp. 117–171]. The hot hydrogen is not gravitationally bound and can be coarsely extrapolated to Galileo positions by assuming an inverse-square radial dependence beyond 3500 km. The atomic oxygen is mostly gravitationally bound and the densities are considerably less than those for hydrogen beyond 3500 km.
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16. This particular coordinate system is chosen because of the convenience of computing the positions of the plasma samples in phase space. Specifically, the V_3-axis is directed parallel to $\mathbf{B}$, and V_2 is parallel to $\mathbf{B} \times \mathbf{V}_s$, where $\mathbf{V}_s$ is the antisolar direction in a right-handed Cartesian coordinate system. The gyration speed is $V_g = |\mathbf{V}_s \times \mathbf{B}|/B$.
17. Pickup ions in the vicinity of comet Halley have been reported to be scattered in velocity space after their initial gyromotion in a ring [T. Mukai, W. Miyake, T. Terasawa, M. Kitayama, K. Hirao, *Nature* **321**, 299 (1986)].
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19. To obtain an estimate of the anticipated densities of pickup hydrogen ions, we use the atmospheric model for atomic hydrogen (*13*) and assume a one-dimensional geometry with $\mathbf{V}_s \cdot \mathbf{B} = 0$ and a radial column density of atomic hydrogen. Then the corresponding ion density is $1.5 \times 10^{11}/V_s\tau R$, where $V_s = 4.5 \times 10^7$ cm s^{-1}, R is the radial distance from Venus center to the spacecraft in units of Venus radii, and τ is the lifetime of atomic hydrogen, 1.2×10^6 s [P. D. Feldman, in *Comets*, L. L. Wilkening, Ed. (Univ. of Arizona Press, Tucson, 1982), pp. 461–479].
20. We acknowledge discussions with M. G. Kivelson, D. A. Gurnett, D. J. Williams, J. D. Mihalov, L. H. Brace, A. I. Stewart, and E. Marsch. M. G. Kivelson and D. A. Gurnett provided data from the magnetometer and plasma wave instrument, respectively. Major contributions to the implementation of the plasma instrumentation at The University of Iowa were made by J. A. Lee, M. R. English, and G. L. Pickett. The authors express their appreciation to the following personnel of the Jet Propulsion Laboratory for their contributions to our efforts: C. M. Yeates, J. R. Casani, W. G. Fawcett, H. W. Eyerly, M. S. Spehalski, W. J. O'Neil, R. F. Ebbett, T. V. Johnson, and S. J. Bolton. This research was supported in part at The University of Iowa by the Jet Propulsion Laboratory under contract 958778.

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Images from Galileo of the Venus Cloud Deck

Michael J. S. Belton, Peter J. Gierasch, Michael D. Smith, Paul Helfenstein, Paul J. Schinder, James B. Pollack, Kathy A. Rages, Andrew P. Ingersoll, Kenneth P. Klaasen, Joseph Veverka, Clifford D. Anger, Michael H. Carr, Clark R. Chapman, Merton E. Davies, Fraser P. Fanale, Ronald Greeley, Richard Greenberg, James W. Head III, David Morrison, Gerhard Neukum, Carl B. Pilcher

Images of Venus taken at 418 (violet) and 986 [near-infrared (NIR)] nanometers show that the morphology and motions of large-scale features change with depth in the cloud deck. Poleward meridional velocities, seen in both spectral regions, are much reduced in the NIR. In the south polar region the markings in the two wavelength bands are strongly anticorrelated. The images follow the changing state of the upper cloud layer downwind of the subsolar point, and the zonal flow field shows a longitudinal periodicity that may be coupled to the formation of large-scale planetary waves. No optical lightning was detected.

The Solid State Imaging (SSI) camera on Galileo returned 77 useful images from Venus documenting the dynamical state of the cloud tops during the week after the encounter on 10 February 1990 universal time (UT). The geometry of the encounter (*1*) and the ability of the SSI camera (*2*) to image in the near-infrared (NIR) and the violet allowed an imaging sequence that probed to different depths in the cloud layers and that could follow the evolution of small-scale dynamical phenomena in the atmosphere as it flowed through the subsolar region and downwind toward the afternoon terminator. This region of the atmosphere has not undergone detailed exploration by previous missions to Venus.

Mariner 10, Pioneer Venus, Vega balloon, and recent ground-based infrared observations have provided a great deal of information about the dynamical state of the venusian clouds (*3–5*). The pressure level where the short-wavelength contrasts are formed is ~50 mbar (*6*). This is at a level some 65 to 70 km above the surface, where the temperature is about 230 K. The cloud tops are part of a deep system of haze and cloud layers, consisting of sulfuric acid droplets, that extends upward above the 45-km

M. J. S. Belton, National Optical Astronomy Observatories, Tucson, AZ 85719.
P. J. Gierasch, M. D. Smith, P. Helfenstein, P. J. Schinder, J. Veverka, Cornell University, Ithaca, NY 14853.
J. B. Pollack, K. A. Rages, D. Morrison, NASA Ames Research Center, Moffet Field, CA 94035.
A. P. Ingersoll, California Institute of Technology, Pasadena, CA 91125.
K. P. Klaasen, Jet Propulsion Laboratory, Pasadena, CA 91109.
C. D. Anger, ITRES Research Ltd., Calgary, Canada, T2E 7H7.
M. H. Carr, United States Geological Survey, Menlo Park, CA 94025.
C. R. Chapman, Planetary Science Institute, Science Applications International Corporation, Tucson, AZ 85719.
M. E. Davies, RAND Corporation, Santa Monica, CA 90406.
F. P. Fanale, Institute for Geophysics, Honolulu, HI 96822.
R. Greeley, Arizona State University, Tempe, AZ 85281.
R. Greenberg, University of Arizona, Tucson, AZ 85721.
J. W. Head III, Brown University, Providence, RI 02912.
G. Neukum, Deutsche Luft und Raumfahrt, 8031 Oberpfaffenhofen, Federal Republic of Germany.
C. B. Pilcher, NASA Headquarters, Washington, DC 20546.