RESEARCH ARTICLE

Io's Sodium Cloud

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Abstract. *The first two-dimensional images of the source region of Io's neutral sodium cloud have been acquired by ground-based observation. Observed asymmetries in its spatial brightness distribution provide new evidence that the cloud is supplied by sodium that is ejected nonisotropically from Io or its atmosphere. Complementary, high-time-resolution, calibrated image sequences that give the first comprehensive picture of the variations of the fainter regions of the cloud extending more than 10^5 kilometers from Io were also obtained. These data demonstrate that the cloud exhibits a persistent systematic behavior coupled with Io's orbital position, a distinct "east-west orbital asymmetry," a variety of spatial morphologies, and true temporal changes. The geometric stability of the sodium source is also indicated. Isolation of the cloud's temporal changes constitutes an important milestone toward its utilization as a long-term probe of Io and the inner Jovian magnetosphere.*

Io's unique character among the planet-sized bodies of the solar system was eminently demonstrated during the Voyager encounters with the Jupiter system (*1*). Embedded deep within Jupiter's magnetosphere, bombarded by intense radiation, and characterized by bizarre surface properties, Io is the source of remarkable extended clouds of sodium, sulfur, oxygen, and other species (*2, 3*). These atomic and ionic clouds extend great distances from Io, and their appearance and behavior provide useful insights into the physical conditions of its surface, atmosphere, and plasma environment. Since ground-based observations of these clouds span several years, they provide a valuable framework for interpreting and connecting the in situ "snapshots" returned by planetary probes, which contain comprehensive detail on many other parameters (*4*).

The neutral sodium cloud has been a prime candidate for study because of (i) its brightness in optical wavelengths and hence its accessibility to ground-based observatories; (ii) its value as a tracer of its own source, since it is not swept up by Jupiter's corotating magnetic field as are the ionic clouds; and (iii) the short lifetimes of the neutral atoms against ionization by the local plasma, which make it an indicator of spatial and temporal changes in this plasma (*5, 6*). The cloud extends more than 10^5 km from Io and is asymmetric, with most sodium atoms preceding the satellite in its orbit (*7*). Its optical emissions are excited by resonant scattering of sunlight in the sodium D_2 and D_1 lines at wavelengths of 5890 and 5896 Å (*8*). These optical emissions cease once ionization occurs, a visible indicator of plasma-cloud interactions. The brightness of the cloud is comparable to that of Earth's auroral displays, but contrast is low against the reflected and scattered light fields of Jupiter and Io.

The observed cloud morphologies are determined principally by the characteristics of the source and sink of neutral sodium atoms: the geometry, dynamics, and mass flow rate of sodium injection; and the loss of neutrals to the ionizing plasma. Perturbations by radiation pressure (*9*), by secondary effects of Jupiter's corotating magnetic field (*10*), and doubtless by other factors yet unknown modify the cloud's shape and brightness.

For discussion purposes, the cloud is often divided into three regions (*11*) distinguished by the nature of their spatial association with Io, dynamic signatures, and relative brightness. We follow this tradition but partition the cloud somewhat differently than earlier investigators to facilitate discussion of our specific data set. We designate as the "source region" that part of the cloud coincident with Io's "seeing disk" (the image of Io after degradation by atmosphere and telescope) and including the sodium emission immediately adjacent to it. This is the brightest region of the cloud, having a peak apparent emission rate of tens of kilorayleighs (*12*) and encompassing the sodium source. Region B extends from the source region and moves with Io. Its apparent emission rate is at least a few tenths of a kilorayleigh, and its extent is typically more than 10^5 km. Fainter sodium emission distributed along Io's orbit and elsewhere in the Jovian system comprises region C.

It is the purpose of this research article to provide the first comprehensive picture of the sodium cloud and its behavior, to examine its significance as an extraordinary phenomenon of the Jovian system, and to assess its potential value as a long-term probe of Io and the complex radiation and plasma environment of the inner Jovian magnetosphere.

The Table Mountain Data

Imaging of the sodium cloud at the Jet Propulsion Laboratory Table Mountain Observatory was carried out at the coudé focus of the 61-cm telescope with a silicon imaging photometer system; a Silicon Intensifier Target Vidicon was used as the detector for observations before 1980 and a more sensitive Intensified Silicon Intensifier Target Vidicon thereafter. Images in the D_2 and D_1 emission lines were totally separated by the spectrograph at the detector focal plane (*13*). Two basic imaging techniques were used (*14*), and calibrations were applied (*15, 16*). Data were recorded digitally on magnetic tape for subsequent processing at the Jet Propulsion Laboratory Image Processing Laboratory (*17*).

The only set of calibrated, two-dimensional sodium cloud images spanning an extended time period was obtained at Table Mountain. This image acquisition process began in 1976 (*18*) and continued well beyond the Voyager encounters with the Jovian system. Also unique to this data set are high-time-resolution, calibrated image sequences of the extended cloud and two-dimensional images of the sodium source region. Together, these images provide the first comprehensive picture of the cloud's systematic and temporal variations, its spatial morphologies, and its long-term behavior.

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The Sodium Source Region

A schematic representation of the cloud, which illustrates the derivation of results discussed later in this article, is given in Fig. 1. A comparison of contoured images of region B and the source region at corresponding orbital phases is provided in Fig. 2. The asymmetry of region B may arise from a nonisotropic source, a spatially nonuniform sink, or both. The first model analyses of two-dimensional region B images (*7, 19*) demonstrated that the sodium required to populate this asymmetric cloud had to come primarily from Io's Jupiter-facing hemisphere. Velocity distributions of sodium atoms derived from high-resolution, spectral-line profile data also indicated that sodium was ejected nonisotropically from Io (*20*). It was not possible, however, to determine whether the source itself was nonisotropic or whether the sodium was ionized nonuniformly as it left Io.

Smyth and Combi (*6*) recently incorporated the Voyager measurements of the Io plasma torus, which constitutes the sink for neutral sodium, along with the time-dependent ionization effects associated with its oscillation (*21*) into their model and found that a nonisotropic source was not required to explain the cloud's asymmetry. Although asymmetries in the spatial brightness distributions of Table Mountain source region images (for example, those in Fig. 2) appear to provide direct observational evidence of such a source, their spatial resolution is not sufficient to constrain

Table 1. Systematic variations of region B that occur on a time scale less than or equal to Io's orbital period (42.5 hours).

Variation	Orbital phase dependence (*38*)	Cause
Apparent shape	Geocentric	Viewing perspective (*36*)
Overall brightness	Heliocentric	Solar flux variation (*32*)
East-west orbital asymmetry	Heliocentric; other?	Radiation pressure (*9*); magnetospheric asymmetries (*29*)? Other?
Actual shape; brightness	Magnetic	Variable ionization correlated with magnetic field geometry (*10*)
"Directional features"	Magnetic	Higher velocity sodium ejected into asymmetric, time-variable ionization sink (*30*)

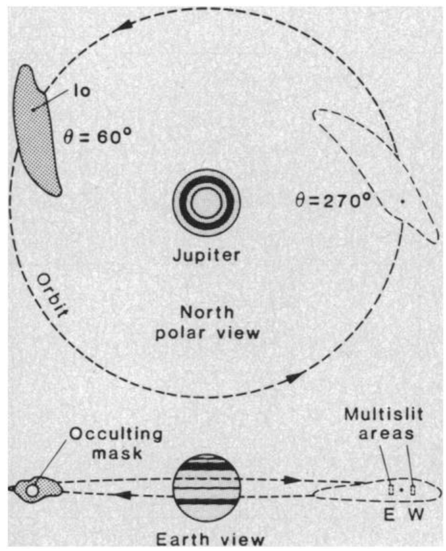

Fig. 1. A schematic representation of region B of Io's neutral sodium cloud as it orbits Jupiter with the satellite (orbital period, 42.5 hours). Io's orbital phase (θ) measured from superior geocentric conjunction (*37*) is indicated. Cloud shapes in the earth view were obtained from observational data, whereas those in the polar view were based approximately on the models of Smyth (*9*). Scale factors were set by the observational data. The areas sampled to obtain the brightness ratios east and west of Io plotted in Fig. 3 and the area obscured by the mask used to occult the bright disk of Io when region B was imaged are also shown. The cloud displays a number of variations described in the text.

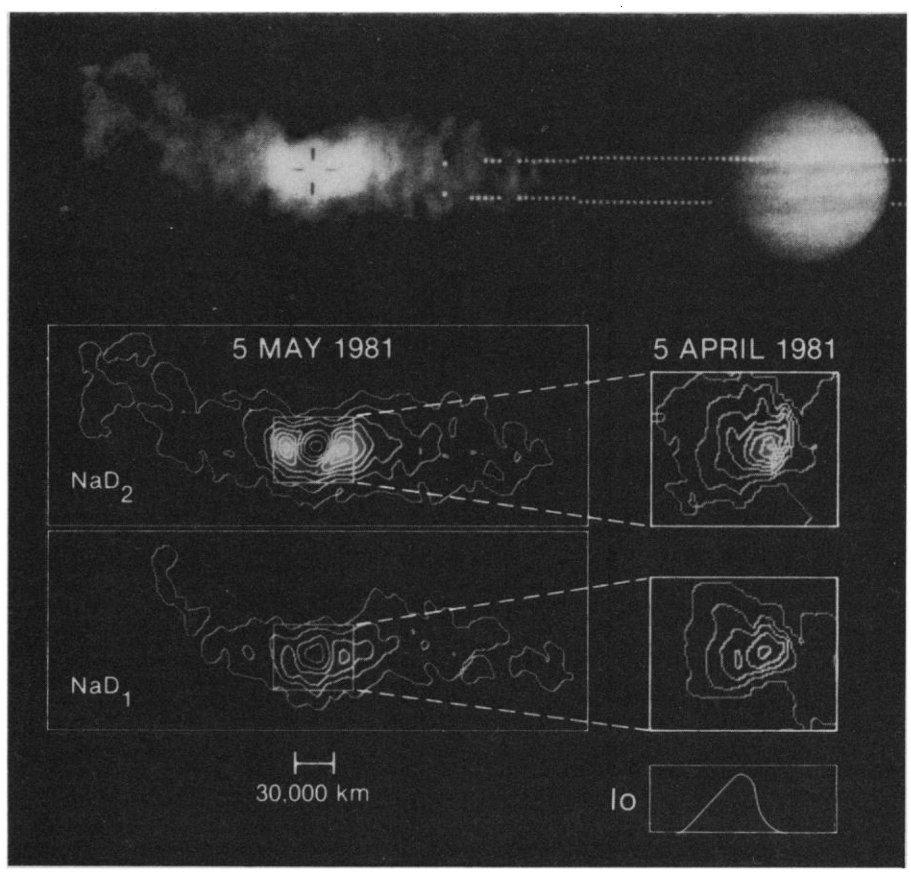

Fig. 2. Images of the source region (right) and region B (left) of Io's neutral sodium cloud compared to investigate the sodium source geometry. Contour intervals are approximately 0.7 kR for 5 May and 5 kR for 5 April, with lowest contours at 0.2 kR and 2 kR, respectively. The dark area within the reference box (16 by 19 arcsec) superimposed on region B is the shadow (in the light of the sodium cloud) of the mask used to occult Io during the exposure. Source region images were taken without a mask (*14*); in the composite picture at the top, the masked area was filled by interpolation. The match between these two types of images is inexact because of differences in the epochs of observation and observing parameters. Orbital phases measured from superior geocentric conjunction (*37*) were 111° on 5 May and 115° on 15 April. Io has a diameter of 3640 km, subtending 1.1 arcsec of the sky at the time of these observations, but the actual image size was greater than 5 arcsec because of degradation by atmosphere and telescope. The profile of Io's reflection spectrum perpendicular to the direction of spectral dispersion is also shown. This spectrum was removed to yield the source region images.

the source geometry and therefore resolve this question (*22*). Indications of nonisotropic sodium ejection are also provided by structure observed in region B (for example, "directional features" discussed in the following section). Both the observational data and the results of theoretical studies favor sputtering of neutral sodium from Io's surface or atmosphere as the principal source mechanism (*23*).

Evidence for stability in the sodium supply rate can be found in measurements of cloud brightness obtained over several years at Table Mountain and elsewhere (*2, 3*). The brightness of source region images is consistent with earlier results obtained by traditional slit spectral techniques. The continued presence of the cloud was questioned during the Voyager 1 encounter in 1979 because of the apparently null result of the sodium imaging experiment, but insufficient sensitivity was responsible (*24, 25*). Geometric stability of the sodium source is suggested by the consistent repetition of the systematic variations of region B, which are discussed below.

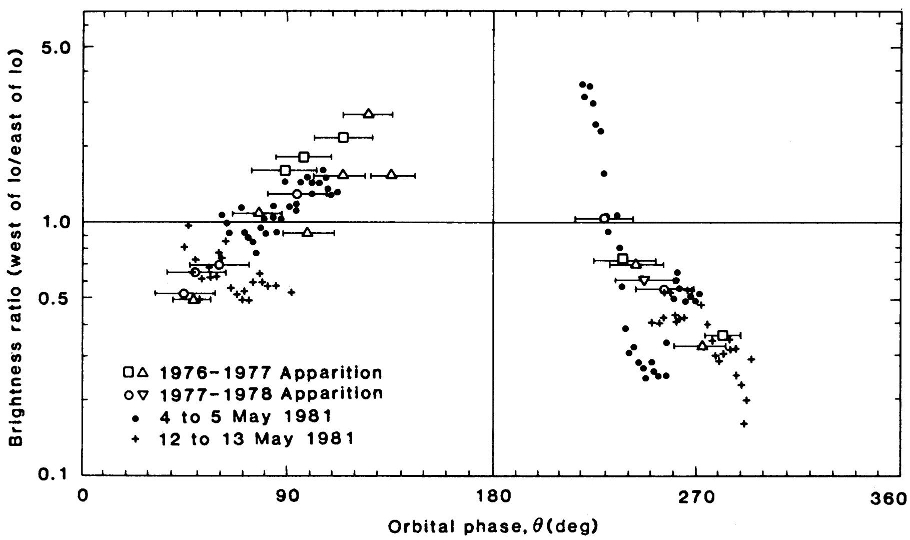

Fig. 3. Ratios of sodium brightness east and west of Io as a function of both time and Io's orbital phase measured from superior geocentric conjunction (*37*). These ratios were derived from the brightness averaged in two rectangular areas (3 by 8 arcsec) located 9 arcsec on either side of the satellite and centered on its orbital plane as shown in Fig. 1. Triangles represent data obtained with multislits. All other data points were derived from two-dimensional images. Horizontal bars indicate the extent of orbital integrations during the multihour exposures required before 1980. The same optical system was used for all observations represented here.

Systematic Variations

The high-time-resolution region B images have now demonstrated that at least five types of systematic variations occur on time scales equal to or less than Io's 42.5-hour orbital period (*26*) (Table 1). A number of these variations were also exhibited in the earlier Table Mountain imaging data.

Brightness ratios derived from region B images form a definite pattern that has persisted since 1976, demonstrating overall cloud stability (Fig. 3). This pattern reflects primarily viewing perspective effects, but true variation in the cloud east and west of Jupiter is also present. This east-west orbital asymmetry is clearly evident in the two-dimensional images, where there is an absence of expected mirror symmetry at orbital phases separated by 180° (*27, 28*). Radiation pressure (*9*) and perhaps also real asymmetries in the inner magnetosphere of Jupiter, for which there is supporting evidence (*29*), are responsible.

Dispersion in the data displayed in Fig. 3 is the result of differences in the observing parameters and possibly subtle changes in the cloud as well. Significant departures from the basic pattern of variation are correlated with either systematic changes occurring on time scales different from Io's orbital period or identifiable structure. On 12 May 1981, for example, the departure was caused by a "directional feature" (*30*), which evolved during the imaging sequence.

The cloud brightness perpendicular to Io's projected orbital plane was averaged to show the variation in the observed brightness distribution of sodium as a function of Io's orbital phase (Fig. 4). Viewing perspective again dominates, but there are other changes as well. The decrease in overall brightness on 4 May 1981 when Io was near magnetic longitude 340° appears to be correlated with

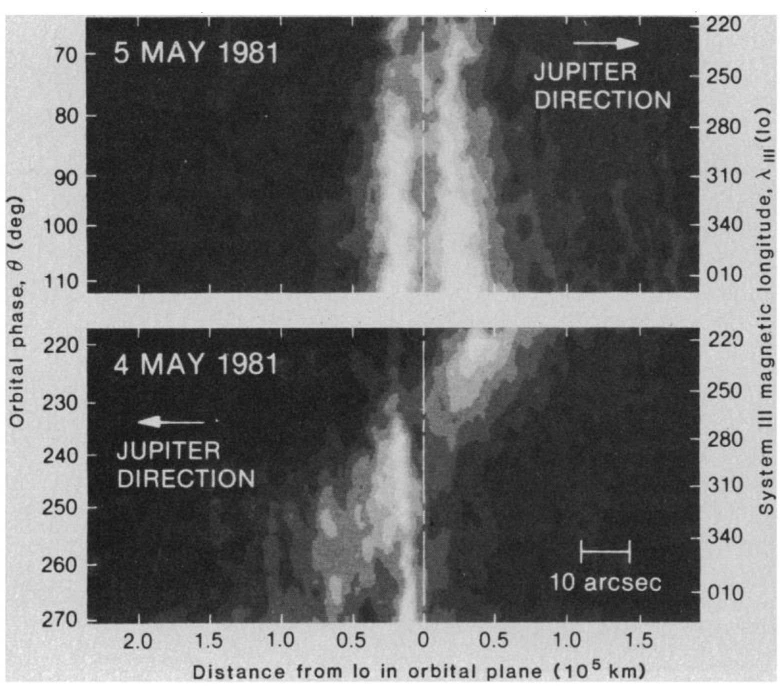

Fig. 4. Sodium cloud brightness in the D_2 line at 5890 Å averaged perpendicular to Io's projected orbital plane. The 61 region B images from which these brightness values were obtained were registered to the position of Io; the resulting brightness matrices were expanded, smoothed, and "contoured" to provide a graphic picture of the time variation in the observed sodium brightness distribution relative to the satellite. A vertical column gives the change in averaged brightness at a fixed distance from Io (in the sky plane) as a function of Io's orbital phase. The dark band encompassing Io's position is the masked region (Fig. 1). Io's passage through Jupiter's magnetic equator occurred at λ_{III} (Io) = 290°. Io's heliocentric orbital phase (*38*) is 7.1° less than its geocentric phase for these observations.

Io's passage through Jupiter's magnetic equator at λ_{III} (Io) = 290°, where enhanced ionization of the sodium of greatest space density is expected to occur. The observed delay is due to the transit times of the sodium atoms from the occulted region of the cloud. Modulation of the cloud brightness correlated with Jupiter's magnetic field geometry was first detected by Trafton and Macy (*31*) in one-dimensional spectral measurements.

The variation in overall cloud brightness due to the periodic (42.5-hour) Doppler shift of the sodium D lines (*32*) has also been observed. This is the first time that it has been clearly demonstrated by two-dimensional region B images. The brightness increase on 5 May 1981 as Io approached eastern heliocentric elongation (Fig. 4) is one example. Characterization of the systematic variations of region B has removed much of the mystery from the cloud's complex behavior, setting the stage for detection of true temporal changes.

Temporal Changes

Several different types of structure have now been detected in region B. Some appear systematically, such as the directional features mentioned earlier (Fig. 5a); others are temporal. Their origins are still unclear, and some systematic correlations with time scales greater than Io's orbital period may yet be established. Among the morphologies first detected in the Table Mountain images are (i) well-defined zones of deficient sodium, due perhaps to locally enhanced ionization, (ii) "knots" of enhanced brightness, and (iii) "feather-like" extensions outside Io's orbit. The 13 May 1981 image sequence demonstrates the first of these, an evolving, almost-linear truncation of the cloud southwest of Io (Fig. 5b). The second of these was demonstrated on 4 May 1981, when a particularly bright area of unknown origin developed east of Io, just outside the boundary of the occulting mask. The third type of feature was first observed during the Voyager 1 encounter with Jupiter (*24*) and is also present in some of the high-time-resolution data. Variations in the shape of the cloud were also observed between 4 to 5 May and 12 to 13 May 1981 and are believed to be temporal. Modeling studies are proceeding (*33*) in an effort to better understand the physical basis of these effects. Temporal changes in the Jovian magnetosphere have been indicated by a variety of observations (*34*).

Conclusions

Io's neutral sodium cloud owes its existence to the bizarre character of the satellite itself and to its interactions with the radiation and plasma environment of the inner Jovian magnetosphere. That this enormous glowing cloud retains its basic character year after year as it moves with Io seems quite remarkable. Yet this is the case, as demonstrated by the images obtained from Table Mountain Observatory.

The Table Mountain data show further that the cloud has a complex but predictable systematic variation, a source that appears geometrically stable, and identifiable temporal changes. The first two-dimensional images of the source region provide new evidence that the cloud is supplied by sodium ejected nonisotropically from Io or its atmosphere.

We anticipate that the cloud's variations will prove to be diagnostic of spatial and temporal changes in Io's environment and perhaps also of activity on Io as well. Earlier spectroscopic observations of the faintest region of the cloud have already demonstrated a relation between its variability and the state of the Jovian plasma (*35*). Future study of the sodium source geometry and supply rates based on the Table Mountain data are also expected to yield useful constraints on Io's atmosphere. A definitive understanding of the sodium source mechanism must, however, await observations of greater spatial resolution complemented by detailed velocity information. The characteristics of the extended cloud (in particular, its basic stability and display of temporal structure together with its accessibility to ground-based observatories and its opportune spatial association with Io) strongly recommend its use as a long-term probe of Io and its environment. The state of model development is such that "calibration" of this probe appears feasible.

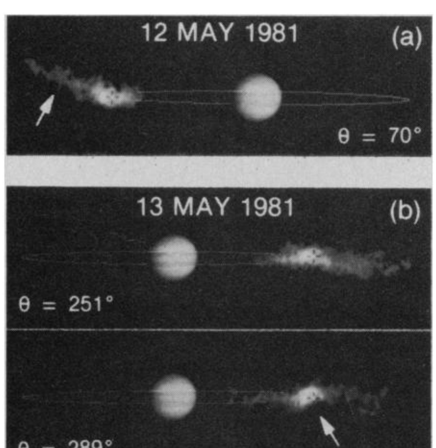

Fig. 5. Examples of two types of cloud structure: (a) a "directional feature" outside Io's orbit and (b) a zone of deficient sodium which developed southwest of Io during the image sequence represented here. Directional features have been correlated with Io's magnetic longitude (*30*). The "zone of deficiency" is a type of structure never before reported. Images obtained a week before the 13 May sequence at corresponding orbital phases appeared markedly different.

Our long-term goals have been (i) to develop the capability to routinely invert observed cloud properties into physical parameters that help describe Io, its atmosphere, and its plasma environment and (ii) to use the cloud to monitor changes in these parameters. The observational results reported here represent significant progress toward completing the first major step: to characterize the cloud's systematic changes, isolate its temporal variations, determine its long-term behavior, and better understand the nature of its source.

References and Notes

1. E. C. Stone and A. L. Lane, *Science* **204**, 945 (1979); *ibid.* **206**, 925 (1979); B. A. Smith *et al.*, *ibid.* **204**, 951 (1979); *ibid.* **206**, 927 (1979); G. E. Hunt, *Nature (London)* **280**, 725 (1979).
2. C. B. Pilcher and D. F. Strobel, in *Satellites of Jupiter*, D. Morrison, Ed. (Univ. of Arizona Press, Tucson, 1982), pp. 807–845.
3. R. A. Brown, C. B. Pilcher, D. F. Strobel, in *Physics of the Jovian Magnetosphere*, A. J. Dessler, Ed. (Cambridge Univ. Press, New York, 1983), pp. 197–225.
4. These include emission characteristics of the Io plasma torus (that is, a doughnut of plasma inclined ~7° to Io's orbit) in wavelength regions inaccessible from Earth, directly measured plasma properties, the structure of Jupiter's magnetic field, and details of Io's surface. Voyager measurements were addressed in special issues of *Science* (1 June 1979 and 23 November 1979).
5. Ionization caused by the impact of thermal electrons is the dominant process by which neutral sodium is lost from the cloud [R. W. Carlson, D. L. Matson, T. V. Johnson, *Geophys. Res. Lett.* **2**, 469 (1975)]. Typical lifetimes of the neutral atoms are only a few hours (*3*, *6*), and so it is possible to detect changes along the orbital path.
6. W. H. Smyth and M. R. Combi, *Bull. Am. Astron. Soc.* **15**, 810 (1983).
7. D. L. Matson, B. A. Goldberg, T. V. Johnson, R. W. Carlson, *Science* **199**, 531 (1978).
8. D. L. Matson, T. V. Johnson, F. P. Fanale, *Astrophys. J.* **192**, L43 (1974).
9. W. H. Smyth, *ibid.* **234**, 1148 (1979); *ibid.* **264**, 708 (1983).
10. For example, the spatial correlation of ionizing plasma with the magnetic field geometry. Maximum ionization occurs near the centrifugal equator: 7° for Jupiter [M. H. Acũna, K. W. Behannon, J. E. P. Connerney, in *Physics of the Jovian Magnetosphere*, A. J. Dessler, Ed. (Cambridge Univ. Press, New York, 1983), p. 6].
11. Cloud region nomenclature was first proposed by R. A. Brown *et al.* [*Astrophys. J.* **200**, L49 (1975)] and later updated (*2*).
12. The apparent emission rate (in rayleighs) is the measured surface brightness (in photons per second per square centimeter per steradian) multiplied by $4\pi \times 10^{-6}$ [J. W. Chamberlain, *Physics of the Aurora and Airglow* (Academic Press, New York, 1961) pp. 569–571].
13. The match between detector and spectrograph was ideal for imaging the sodium cloud (spatial scale, 0.8 arcsec per pixel; spectral resolution, 0.07 Å per pixel. The 256 by 256 pixel image frame subtended ~200 by 200 arcsec, encompassing region B. Io's projected orbital plane was aligned perpendicular to the direction of spectral dispersion. Images of the cloud in the

D_2 and D_1 emission lines were separated by ~72 arcsec.
14. To record region B, it was necessary to mask the bright disk of Io at the input focal plane of the spectrograph and use relatively long exposures: typically 2 to 3 hours prior to 1980 and 10 minutes thereafter. To record the source region against the bright disk of Io, exposures of 3 to 5 minutes were made at a lower detector sensitivity setting and without a mask. The result was a pair of images of this brightest part of the cloud superimposed on Io's solar reflection spectrum, which was subsequently "modeled" with that of another Galilean satellite recorded close in time and removed.
15. A stable and uniform light source (with National Bureau of Standards calibration) was imaged to provide measures of nightly detector stability and long-term detector performance. Io's solar reflection spectrum was used for direct calibration of cloud brightness and was coincident with the source region images. Problems associated with traditional measurement techniques [see (*16*)] were essentially eliminated.
16. J. T. Bergstralh, D. L. Matson, T. V. Johnson, *Astrophys. J.* **195**, L131 (1975).
17. Many of the subroutines used were originally developed for the reduction of spacecraft imaging data. Basic steps involved the removal of both instrumental effects and sky background contamination, followed by quantitative analysis and image enhancement.
18. The first two-dimensional images of the cloud were obtained at Table Mountain in 1976 with the direct imaging technique described here [B. A. Goldberg, D. L. Matson, T. V. Johnson, *Eos* **58**, 429 (1977); (*7*)] and by a Harvard group who used a multislit technique [F. J. Murcray, thesis, Harvard University (1978); F. J. Murcray and R. Goody, *Astrophys. J.* **226**, 327 (1978)].
19. W. H. Smyth and M. B. McElroy, *Astrophys. J.* **226**, 336 (1978).
20. R. W. Carlson, D. L. Matson, T. V. Johnson, J. T. Bergstralh, *ibid.* **223**, 1082 (1978).
21. The plasma torus has a period of oscillation of 13 hours with respect to Io (*4, 10*).
22. We deconvolved the source region images, using point spread functions derived from intensity profiles of Io's solar reflection spectrum with a technique developed by J. J. Lorre [*Comput. Vision Gr. Image Process.* **23**, 334 (1983)]. Deconvolved images were asymmetric, but interpretation was uncertain. Further problems of interpretation arise because of questions concerning the detectability of sodium emission originating from that part of the cloud gravitationally bound to Io [R. A. Brown, R. M. Goody, F. J. Murcray, *Astrophys. J.* **200**, L49 (1975)].
23. This mechanism is discussed by Matson *et al.* (*8*). Current arguments perhaps favor atmospheric sputtering because of apparent difficulties in obtaining sufficient yields of sodium from Io's surface. A recent discussion of source mechanisms is given by C. B. Pilcher, W. H. Smyth, M. R. Combi, J. H. Fertel, *Astrophys. J.*, in press.
24. A new analysis of the Voyager 1 sodium data (P. K. Kupferman, personal communication) has placed the detection threshold at about 100 kR, significantly above the peak brightness measured in the source region images. Furthermore, "normal" region B images were obtained from Table Mountain within hours of the Voyager 1 closest approach to Io (*25*).
25. B. A. Goldberg *et al.*, *Icarus* **44**, 305 (1980).
26. A color movie entitled "Dynamics of the Io Sodium Cloud" was produced by B. Goldberg from these images for the National Air and Space Museum, Smithsonian Institution, Washington, D.C. This film clearly shows the range of region B variations. Composite pictures in a number of the figures were derived from single movie frames.
27. An optically thin cloud moving unchangingly with Io would mirror itself to the observer at orbital angles separated by 180°. Since the cloud appears to be optically thin even near Io, as indicated by preliminary D_2:D_1 ratio maps derived from the Table Mountain images, the east-west asymmetry must be real. An asymmetry in the sodium brightness measured near Io (*28*) may follow in part from the cloud geometry.
28. J. T. Bergstralh, D. L. Matson, T. V. Johnson, *Astrophys. J.* **190**, L107 (1975).
29. For example, an east-to-west difference in the brightness and morphologies of the ionic cloud emissions in the Io torus was measured, with the western emission being brightest [J. S. Morgan, *Bull. Am. Astron. Soc.* **15**, 811 (1983)]. Further discussion of Io plasma torus asymmetries is given by T. W. Hill, A. J. Dessler, and C. K. Goertz [in *Physics of the Jovian Magnetosphere*, A. J. Dessler, Ed. (Cambridge Univ. Press, New York, 1983), p. 393].
30. Elongated features discovered by C. B. Pilcher [see B. K. Hartline, *Science* **208**, 384 (1980)] are observed outside Io's orbit and alternate north and south of the satellite plane [C. B. Pilcher, W. H. Smyth, M. R. Combi, J. H. Fertel, *Bull. Am. Astron. Soc.* **15**, 810 (1983); (*23*)]. These features are clearly evident in the Table Mountain region B images (Fig. 5a) and provide some indication of a nonisotropic source.
31. L. Trafton and W. Macy, Jr., *Astrophys. J.* **202**, L155 (1975); L. Trafton, *ibid.* **215**, 960 (1977).
32. Sodium emission lines are Doppler-shifted with respect to the Fraunhofer absorption lines in the solar spectrum so that the amount of sunlight available to excite the sodium atoms varies periodically (*8*). The solar excitation function is maximum at the heliocentric elongations (*38*), but the observed brightness at a given point on the cloud is a function of both the available sunlight and the column density of emitting sodium atoms.
33. A collaborative modeling analysis of the Table Mountain images has been initiated between W. H. Smyth and B. A. Goldberg.
34. For example, significant changes have been detected in the ultraviolet and extreme ultraviolet emissions of the Io plasma torus [J. D. Sullivan and G. L. Siscoe, in *Satellites of Jupiter*, D. Morrison, Ed. (Univ. of Arizona Press, Tucson, 1982), p. 848; (*2*)].
35. Y. Mekler and A. Eviatar, *J. Geophys. Res.* **83**, 5679 (1978).
36. Also depends on cloud brightness and parameters of observation such as detection threshold.
37. This occurs when Io is farthest from Earth in the line of sight from Earth to Jupiter.
38. Geocentric orbital phase is measured from superior geocentric conjunction (*37*). Heliocentric phase is measured analogously with respect to the sun-Jupiter line. Magnetic orbital phase is measured in a longitude system called System III (1957.0), which describes the rotation of the Jovian magnetic field [for a detailed description, see A. J. Dessler, in *Physics of the Jovian Magnetosphere*, A. J. Dessler, Ed. (Cambridge Univ. Press, New York, 1983), p. 498].
39. We thank R. W. Carlson, D. L. Matson, and D. B. Nash for helpful comments and suggestions; F. E. Bristow, P. L. Jepsen, F. Vescelus, and R. J. Wall for program support; L. E. Hovland, J. C. Mahoney, D. P. Perrenoud, and J. W. Young for technical support; J. C. Hewitt, R. W. Post, and T. Kiriyama for photolab and graphics support; and T. A. Maxwell of the National Air and Space Museum, Smithsonian Institution, for helping to support production of the movie and related data processing. The work described in this article was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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