Chapter 4

Galileo Observations of the Fast Sodium Jet

4.1 Introduction

In this chapter I discuss recent Galileo images of the fast sodium jet at Io. This chapter has been previously published, in somewhat modified form, as Burger et al. (1999). I performed the data reduction and analysis. The modeling in Section 4.4 was a joint effort by myself and J. K. Wilson using the model of Wilson and Schneider (1999). This model is the basis for the neutral cloud model described in Chapter 5.

Since the discovery of the Io sodium cloud more than 25 years ago, planetary astronomers have used imaging and spectroscopic measurements to study the escape of Io's atmosphere (Brown 1974; Trafton et al. 1974). Although only a trace constituent of the material near Io, sodium has proven to be the easiest to observe, with a large cross section for resonant scattering of sunlight and a ground state transition at optical wavelengths (589.0,589.6 nm). For most atmospheric escape processes, sodium is considered a good tracer of the more abundant species such as sulfur dioxide (Ballester et al. 1994) or its dissociation products oxygen or sulfur.

One escape process, which does not have substantial non-sodium component due to the fact that sodium is the dominant constituent in Io's ionosphere (Wilson and Schneider 1999), offers important insights into the atmosphere of Io and the nature of Io's interaction with Jupiter's magnetosphere. A prominent jet, called the "directional feature," projects roughly radially outward from Jupiter (Goldberg et al. 1984) (Figure 4.1). It tilts slightly north or south of the equatorial plane depending on the tilt of Jupiter's magnetic field at Io.

Wilson and Schneider (1999) have recently offered a new explanation for the jet. Based on extensive modeling of ground-based images and spectra, they conclude that the jet is a manifestation of ionospheric escape at Io. The escape is driven by the electrodynamic potential of 411 kV induced across Io by its motion through Jupiter's magnetic field (Goldreich and Lynden-Bell 1969; Dessler 1983). The electric field is directed radially outward from Jupiter and perpendicular to the magnetic field. Radio occultations by spacecraft have revealed a global ionosphere capable of conducting mega-ampere currents in response to this potential (Hinson et al. 1998). The dominant ionospheric ion is Na^+ by virtue of sodium's very low ionization potential (Summers and Strobel 1996). Sodium ions are driven by Pedersen currents radially outward from Jupiter. Ions on the sub-Jupiter side of Io are driven to the surface and cannot escape; those on the anti-Jupiter side are not blocked. Some of these escaping ions are neutralized by charge exchange reactions and become fast sodium atoms directed away from Io at velocities of tens of km sec^{-1}. The sodium atoms preserve their ion motion at the moment of charge exchange, which includes a substantial gyrovelocity perpendicular to the local magnetic field. The plane of gyromotion defines the orientation of the jet. Sodium-bearing molecular ions, known to produce fast sodium features farther from Io (Wilson and Schneider 1994), may contribute sodium atoms to the directional feature. Sodium ejected from Io's ionosphere adds to the extended disk of sodium atoms observed as far as 500 Jovian radii from Jupiter (Mendillo et al. 1990). For a more complete explanation of this process, see Wilson and Schneider (1999).

Prior to the Galileo spacecraft observation, only ground-based telescopes had observed the sodium jet. Scattered light from Io prevents measurements much closer than $\sim 0.25\ R_J$ and atmospheric blurring limits spatial resolution to about 4 R_{Io} Although the Voyager spacecraft carried a narrowband sodium filter, its detector lacked the sensitivity

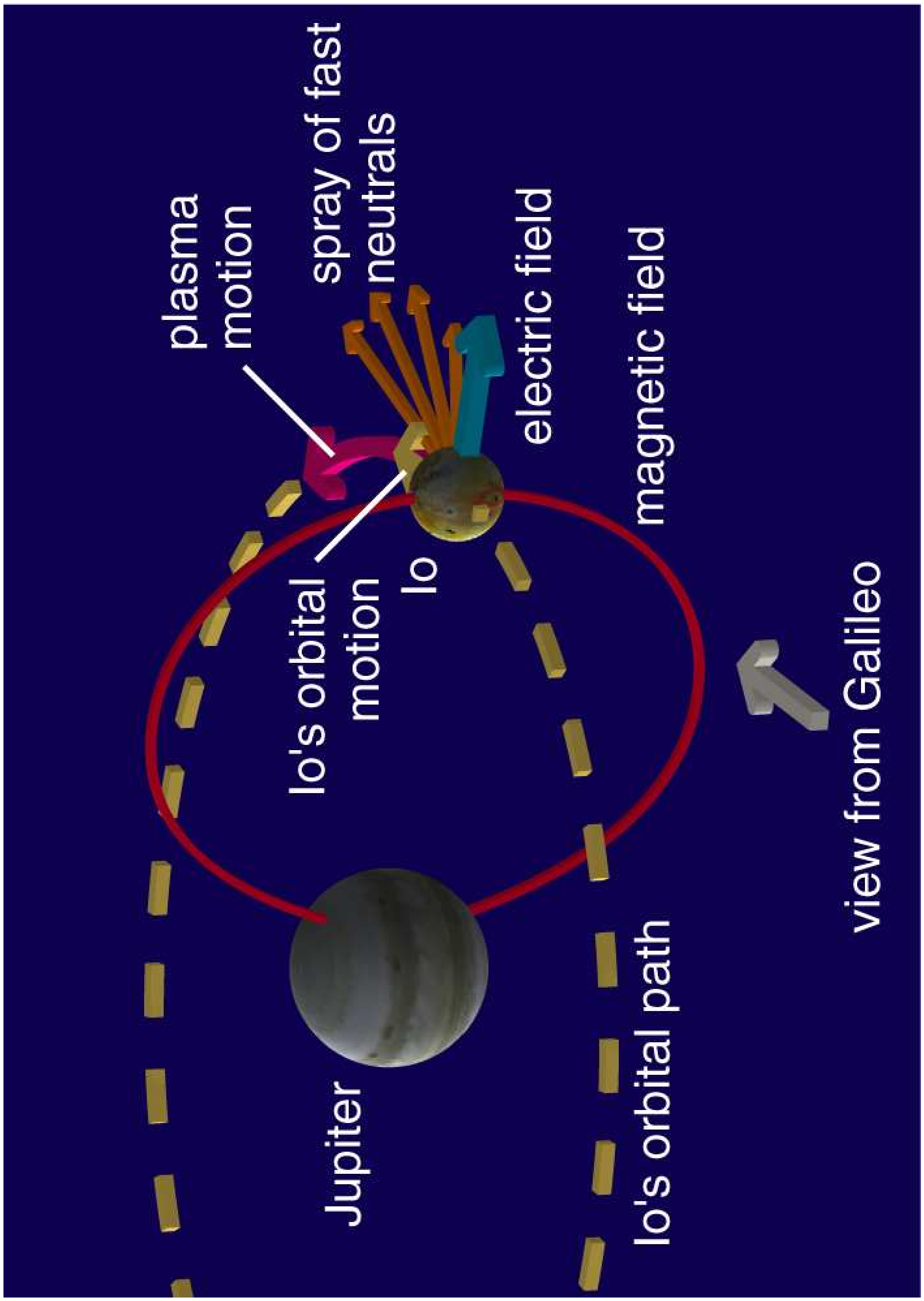

Figure 4.1 The relative directions of the electric field (shown in blue) , magnetic field (red), and motions of ions (pink) and fast neutrals (orange) at Io. Escaping ionospheric sodium creates a spray of fast sodium atoms lying in the plane normal to the Jovian magnetic field line through Io. Galileo viewed the spray almost edge-on giving it the appearance of a jet.

to detect sodium (Goldberg et al. 1980). Galileo therefore offered the first opportunity to trace the jet back to its source region. One of the greatest uncertainties in Wilson and Schneider's model is the overall size of the source region: does it span Io's entire disk, or is it confined to more localized regions?

4.2 Observations

The Galileo team faced numerous challenges in designing an appropriate observation to detect faint emission from the sodium cloud so close to Io's bright disk. Since the sodium cloud glows by resonantly scattering sunlight, it was not possible to image the sodium cloud in Jupiter's shadow, a technique which has revealed numerous other atmospheric emissions (Geissler 1999). Instead, the observations were optimized for faint emission detection by observing Io's night side while the Galileo spacecraft lay in Jupiter's shadow. Io's disk was placed on the edge of the CCD detector in order to move the small sunlit crescent out of the field of view. A sequence of two 13-second exposures was taken on 9 November 1996 just after the C3 encounter (These images are publicly available through the Planetary Data System Imaging Node). The distance of the spacecraft from Io was 2.1×10^6 km giving a spatial scale of 44 km pixel^{-1}. Io's magnetic longitude at the time of the observation was $\lambda_{\rm III} = 34°$.

The image taken by Galileo is a double exposure of Io, with Io repositioned and the filter changed between exposures. The upper image uses a clear filter (effective wavelength = 611 nm, bandpass = 440 nm), and the lower one a green filter (559 nm, bandpass = 65 nm) (Belton et al. 1992). The images were converted from raw counts to intensity units using the GALSOS routine in the VICAR image reduction software package available from the Jet Propulsion Laboratory. Because Na D line emission is at the edge of the green filter bandpass, intensity attributed to sodium must be additionally corrected for the decreased filter efficiency by a factor of ~ 1.6 relative to the peak filter transmission. No such correction was necessary for the clear filter exposure.

4.3 Analysis

Several features appear in the images which complicate the analysis of sodium. The sunlit crescent of Io is just off the frame, and a Jupiter-lit crescent appears in the image. These features are orders of magnitude brighter than any Iogenic emissions and contribute to scattered light in the image. An unfortunate surprise is the volcanic plume Prometheus in full sunlight on Io's day side rising $\gtrsim$ 75 km above Io's surface and beyond Io's limb, scattering sunlight directly into Galileo's cameras. Nonetheless, the "directional feature" due to sodium is marginally visible in the raw data.

The relative contributions of scattered light from the sunlit crescent, the plume, and Io's atmosphere itself are difficult to gauge, but can be approximated *in toto* by assuming azimuthal symmetry around Io. We fit this component of the light profile as the sum of two independent power laws centered on the disk of Io in each image; each pixel receives scattered light through both filters due to the double exposure. Stars and other bright spots in the images were removed before fitting, as were the directional features. Light scattered through the broad clear filter dominates most of the field of view. The scattered light falls off as $r_1^{-0.8\pm0.2}$, where r_1 is the distance from Io in the clear image. Since the dominant source of error is the non-uniformity of the background, error bars were determined by manually adjusting the fit parameters to minimally acceptable limits. Scattered light centered on the plume in the green image falls off as $r_2^{-1.1\pm0.2}$, steeper than in the clear filter. The intensity ratio between the two filters is consistent with the bandpass differences.

The steeper power law observed in the green filter is consistent with the sodium emission expected from Io's extended atmosphere, whose intensity falls off as $r^{-2.3}$ (Chapter 3). Such emission is more likely to be observable through the green filter, whose 7 times narrower bandpass offers better contrast of sodium emission versus scattered light despite the 1.6 times lower filter transmission at the sodium D lines. At the current level of analysis it is not possible to extract more quantitative information on the sodium corona. Interpretation is complicated, as the corona is optically thick near Io, and Galileo viewed Io's "night side". Nonetheless, the ring of emission surrounding Io in both images is clearly Iogenic. The observed intensity is consistent with either continuum scattering by dust around Io or a sodium corona with column density $\gtrsim 6 \times 10^{11}$ cm^{-2} at Io's surface (The lower limit on sodium column density is found by assuming the cloud is optically thin all the way to the surface). As the known sodium corona has a density greater than this, the latter explanation is preferred. We postpone further discussion of this feature to a future paper.

Figure 4.2 shows the image with scattered light subtracted revealing the "jet" originating at Io and extending to the right and slightly downward. The jet appears clearly in both images. The clear filter image has a higher signal to noise ratio (S/N) in regions where contrast against scattered light was not a problem, i.e., far from Io. The green filter provides higher S/N where the reduced sensitivity is not the dominant problem, i.e., closer to Io. The jets cannot be an artifact of the scattered light subtraction, as the background is azimuthally symmetric about the two plumes. These images provide the best spatial resolution ever achieved of the directional feature as well the closest detection to Io. The magnetic field line through Io is shown in figure 2. As predicted by the model of Wilson and Schneider, the orientation of the directional feature is roughly perpendicular to the magnetic field.

4.4 Discussion

Quantitative measurements of the jet properties in the background subtracted image provide key constraints on the escape mechanism. For each radial position along the jet, we extracted an azimuthal profile centered on Io. Near the position of the jet, we fit a linear background to the azimuthal variations in the scattered light profile, and estimated the position, peak brightness and full-width-at-half-maximum (FWHM)

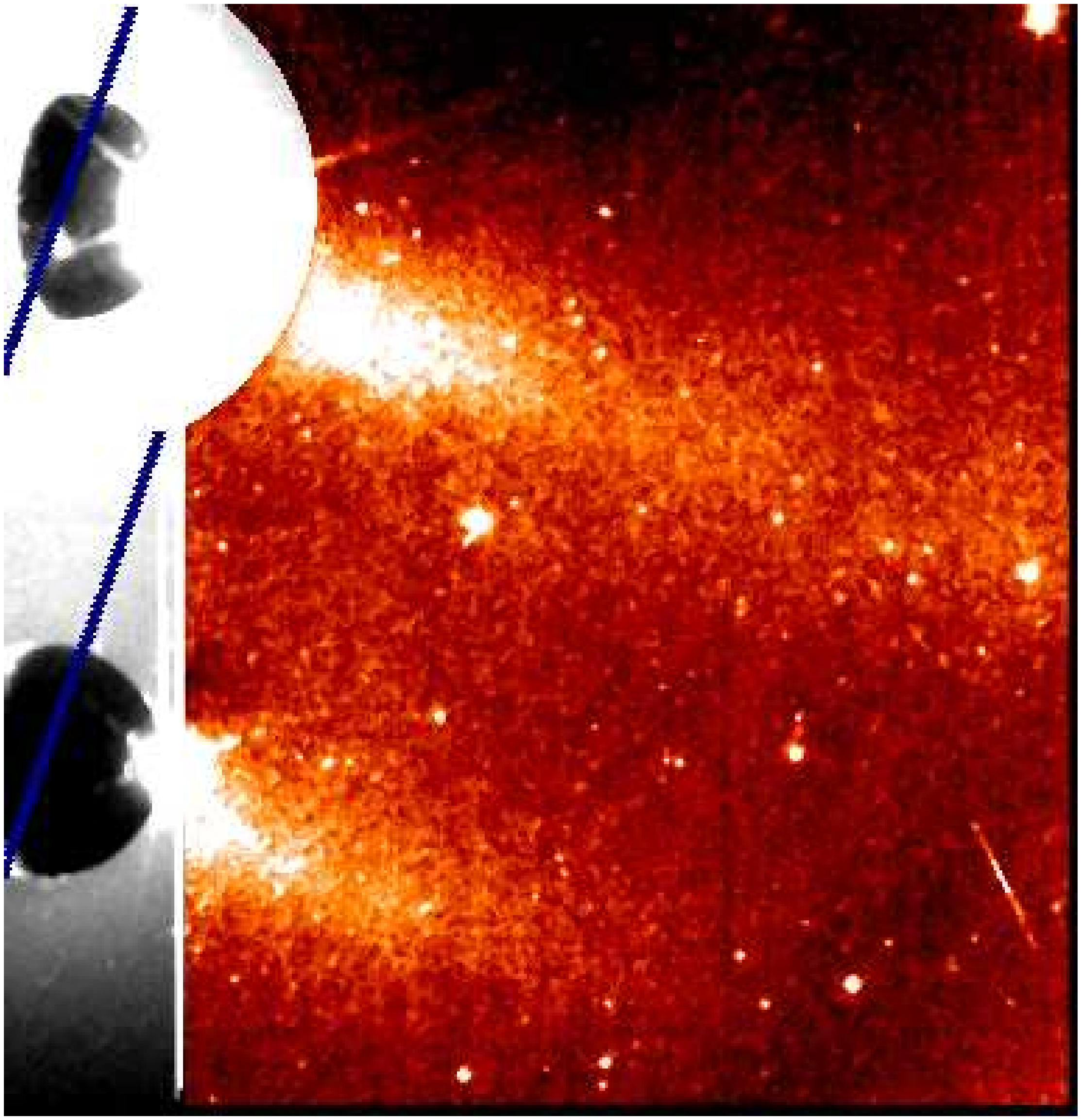

Figure 4.2 The background-subtracted Galileo image showing the fast sodium jet extending down and to the right (false-color red). The top image is primarily through the clear filter; the bottom through the green filter. Io's disk and the region immediately surrounding Io are shown as seen in the raw image using greyscale. Iogenic emission (probably due to sodium, see text) contributes to emission surrounding Io's disk. The bright region at the right edge of Io's disk is due to scattered light from the Prometheus plume. The illuminated crescent on the left edge of Io is sunlight reflected off of Jupiter onto Io. The Pele hot spot can be seen on Io's disk through the clear filter. The fast sodium is brighter in the clear exposure than the green due to the differing filter transmission at 590 nm. The jovian magnetic field line through Io is shown in blue.

of the jet. Errors in these quantities were derived by using the marginally acceptable power-law fits to the residual scattered light background; the derived quantities are not sensitive to the background values chosen. The highest quality measurements were obtained at 3 R_{Io}.

Perhaps the most significant measurement is the latitudinal width of the jet. Previous studies of Io's atmospheric loss processes have been divided over whether to consider Io's atmosphere at least as large as Io itself (larger, in the case of an extensive atmosphere with an exobase well above the surface), or significantly smaller than Io (due to a patchy atmosphere concentrated around Io's volcanoes, and absent over the frigid poles) (Spencer and Schneider 1996). The sodium jet is clearly in the latter category. The green filter image offers the best measurement close to Io of 1.1±0.1 R_{Io} at 3 R_{Io}, substantially narrower than Io's diameter. The data are not of sufficient quality to determine how the width changes with distance. Due to the complex velocity structure of the jet close to Io, the supply rate is estimated by comparison of the measured brightness of sodium with simulations of the jet with a known supply rate. The supply rate in the jet is estimated to be $4.8 \pm 1.0 \times 10^{25}$ atoms sec^{-1}, consistent with previous estimates measured farther from Io (Schneider et al. 1991b; Wilson and Schneider 1999).

We can constrain the size of the source region by comparing the Galileo data to profiles simulated using the model of Wilson and Schneider (1999) under the Galileo observing conditions. Figure 4.3a compares the Galileo green filter data with simulated azimuthal intensity profiles at 3 R_{Io} of jets that result from a point source on Io and from an ionosphere covering Io's anti-Jovian hemisphere. Neither model matches the data well. The data are most consistent with an ionosphere concentrated within 35° of the equator (Figure 4.3b). The source region could be even smaller if other processes (such as the bending of magnetic field lines by the Io interaction) are included; such analysis is reserved for a later paper. The present result represents an upper limit on the latitudinal extent of the ionosphere.

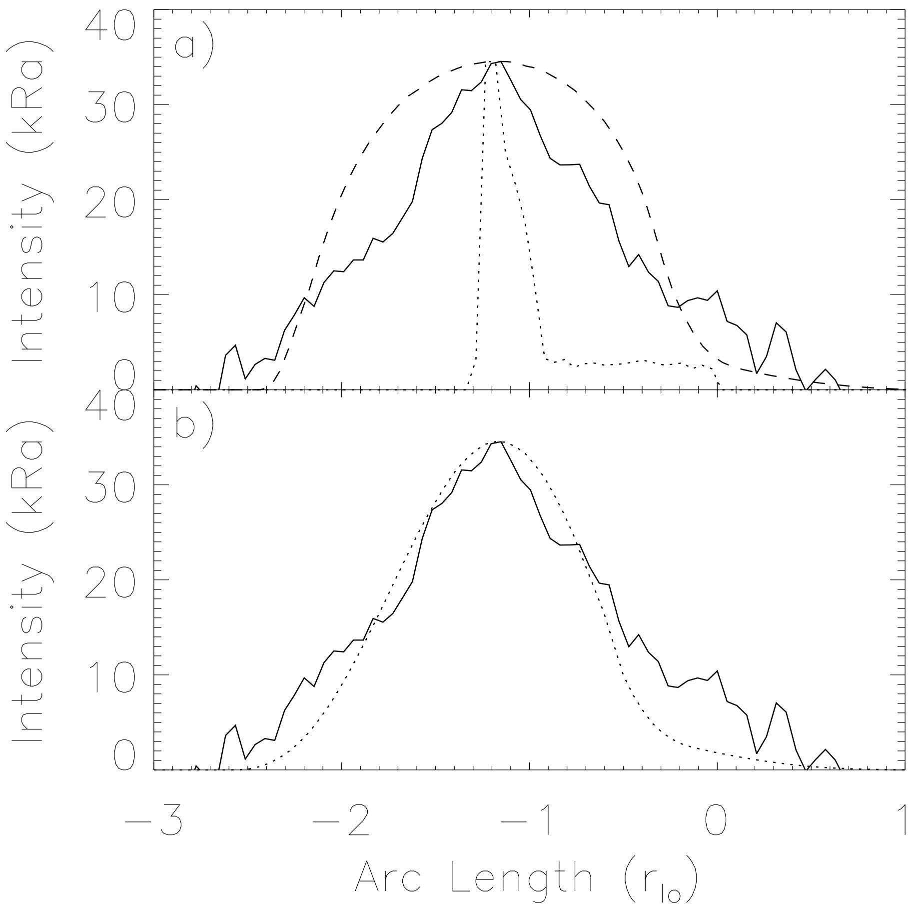

Figure 4.3 (a) Intensity profiles through model images and the green filter data at a constant radial distance of 3 R_{Io} from the center of Io. The solid line shows the data (corrected for filter transmission), the dashed line shows a model with a hemispheric source region, and the dotted line shows the jet produced by a point source on Io's anti-Jupiter point. The location of the peaks of the profiles have been adjusted a few tenths of an Io radius so that they are aligned. The cause for this discrepancy is uncertain, but may be related to uncertainties in the subtraction of the sloping background. The full width at half maximum (FWHM) of the data is 1.1 R_{Io} compared to 1.7 R_{Io} for the hemispheric source and 0.2 R_{Io} for the point source, indicating that the source region of the jet is smaller than Io but still covers an extended region. The ionosphere does not extend to the poles. (b) Intensity profiles for the data and the best fit ionospheric distribution. The dashed line shows the intensity resulting from an ionosphere for which the neutral sodium flux at the top of the ionosphere is a Gaussian centered at Io's equator and has a FWHM of 35°. The FHWM of the jet matches the data, showing that Io's ionosphere is concentrated to low latitudes.

Two kinds of source regions are consistent with the observations and the theoretical requirement of a collisionally thick ionospheric layer. The first is an atmosphere concentrated at low latitude (as the model results suggest), expected both due to the preponderance of volcanic outgassing vents there as well as the freezing out of a polar atmosphere. Alternatively, it is conceivable that an individual plume or collection of plumes (and their local atmosphere/ionosphere) could create a large enough ionosphere to create a jet of this size. One possible plume origin is Prometheus, the plume responsible for the scattered light. The Pele eruption (seen in thermal emission near the center of Io's disk through the clear filter) is also a candidate, although its location (just barely on the Jupiter-facing hemisphere) is such that sodium ions created in the plume would most likely not escape Io (Wilson and Schneider 1999).

Further observations of the Io sodium jet are contemplated for future Galileo orbits and the Cassini flyby of Jupiter in late 2000. Without contamination from bright plumes, it may be possible to trace the jet all the way back to its source region in the atmosphere.