In October and November of 1997 the Galileo Solid State Imager (SSI) detected lightning from 26 storms on the night side of Jupiter. More than half the surface area of the planet was surveyed. The data include images of lightning against moonlit clouds (illuminated by light from Io) and images of the same storm on the day and night sides. The spatial resolution ranged from 23 to 134 km per pixel, while the storms ranged in size up to \(1500\) km. Most storms were imaged more than once, and they typically exhibit many flashes per minute. The storms occur only in areas of cyclonic shear and near the centers of westward jets. Latitudes near 50° in both hemispheres are particularly active, although the northern hemisphere has more lightning overall. The greatest optical energy observed in a single flash was \(1.6 \times 10^{10}\) J, which is several times larger than terrestrial superbolts. The average optical power per unit area is \(3 \times 10^{-7}\) W m\(^{-2}\), which is close to the terrestrial value. The limited color information is consistent with line and continuum emission from atomic hydrogen and helium. The intensity profiles of resolved lightning strikes are bell-shaped, with the half-width at half-maximum ranging from \(45\) to \(80\) km. We used these widths to infer the depth of the strikes, assuming that the appearance of each is the result of light scattering from a point source below the cloud tops. We conclude that lightning must be occurring within or below the jovian water cloud. The occurrence of lightning in regions of cyclonic shear has important implications for the dynamics of Jupiter's atmosphere.

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**Key Words:** atmosphere dynamics; Jupiter atmosphere; meteorology.

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**1. INTRODUCTION**

The study of lightning on Jupiter is interesting for several reasons. First, lightning suggests the presence of moist convection, which is an important element in atmospheric dynamics and energy transfer (e.g., Salby 1996, Fig. 1.27). The precise location and intensity of lightning can help to constrain the latitudes, longitudes, altitudes, and magnitudes of this convection. Second, lightning on Jupiter probably requires water in amounts that locally approach or exceed the “solar” value (Yair et al. 1995, Gibbard et al. 1995). This is an important clue to the planet’s global water abundance, which in turn is critical to the theory of Giant Planet formation (Niemann et al. 1998). Third, lightning probably plays a significant role in the production of important trace species such as C\(_2\)H\(_2\), HCN, and CO (Bar-Nun and Podolak 1985). Indeed, the existence of lightning on Jupiter was first predicted by Bar-Nun (1975) to account for the observed abundance of C\(_2\)H\(_2\). Finally, lightning and cloud electrification are of interest for their own sake, and are not well understood (e.g., Golde 1977, Uman 1987). Studying lightning on other planets may help us understand these phenomena both there and on Earth.

Jovian lightning has been observed before. In 1979 the cameras of Voyagers 1 and 2 detected localized bright spots in eight images of the night side of Jupiter (e.g., Cook et al. 1979, Borucki et al. 1982, Magalhães and Borucki 1991, Borucki and Magalhães 1992). These spots represent the first optical
The detection of lightning on a planet other than Earth. Also, on December 7, 1995, the lightning and radio emission detector on the Galileo probe measured radio frequency signals at levels significantly above the probe’s electromagnetic noise (Rinnert et al. 1998, Rinnert and Lanzerotti 1998). These observations can be explained by a lightning-like source on Jupiter at a distance of about 15,000 km (∼12") from the probe site, which was at 6.54° planetocentric latitude and 4.68° west longitude.

Lightning is perhaps best studied through optical imagery, but the relative brightness of Jupiter’s sunlit side means that lightning can be seen with existing cameras only on the night side. The Solid State Imager (SSI) aboard the Galileo orbiter is the only camera since Voyager’s to be in a position to take such images. For the purposes of a lightning study, Galileo has several advantages over Voyager. Since Galileo is an orbiter, it was able to image jovian lightning with a much larger number of frames over a longer period, and to survey substantially more of the planet. Some of Galileo’s images also have better spatial resolution than the Voyager images. In addition, the SSI has a better red response than the Voyager camera, and was able to image lightning at more wavelengths. Finally, the SSI was able to image the night side from above Jupiter’s terminator, when half of the planet beneath the spacecraft was illuminated. This allowed us to image storm locations on the planet’s day side much closer in time to corresponding nightside images.

The paper is organized around key figures and tables. Section 2 shows the area covered by our lightning survey (Figs. 1 and 2), and gives an inventory of all lightning storms (Table I). Section 3 describes the appearance of the storms, and presents examples (Figs. 3–5). Section 4 discusses the relation of lightning to other visible features. We show a lightning storm as it appeared both in the daytime and at nighttime (Fig. 6), and we show the locations of lightning storms in relation to Jupiter’s zonal winds (Fig. 7 and Table II). Section 5 estimates the optical energy of individual flashes (Table III), provides a cumulative frequency distribution of flash energies (Fig. 8), discusses the power and color of jovian lightning (Table IV), and investigates the global flash rate. Section 6 provides an analysis of the depth of the lightning, which we infer from the width of spots observed at the level of the cloudtops (Fig. 9 and Table V). Finally, Section 7 lists some unanswered questions, and discusses some possible implications of our data for the traditional picture of Jupiter’s cloud bands.

2. THE OBSERVATIONS

Galileo’s SSI observed jovian lightning on two successive orbits in 1997. The most panoramic view of the night side occurs when the spacecraft is far from the planet, deep in Jupiter’s shadow, at phase angles near 180° (with the Sun, Jupiter, and the spacecraft lying nearly in a straight line). To make SSI observations near 180° phase, however, the spacecraft must be turned to avoid obscuration by its booms and high-gain antenna. During Galileo’s 10th orbit (the so-called C10 orbit) the spacecraft was turned in this way, and for nearly 7 h beginning at 21:20 Universal Time (UT) on October 5, 1997, the SSI imaged the night side of Jupiter over phase angles varying from 179.3° to 179.8°. The spacecraft was ∼93 jovian radii from the planet’s center, and the resultant resolution was either 67 or 133 km/pixel depending on the camera mode (discussed below).

The highest-resolution views of Jupiter’s night side come when the spacecraft’s phase angle is substantially smaller than 180°, because perijove of Galileo’s orbit is on the day side. Yet at phase angles less than 40°, the dark crescent is too small for effective imaging of the night side. Also, at small phase angles light from the sunlit crescent is scattered into the camera from outside the field of view, and this limits the length of the exposures. At various times during a ∼2-day interval beginning at 18:37 UT on November 5, 1997, during Galileo’s 11th orbit (the so-called E11 orbit), the SSI imaged the day side of Jupiter over a range of phase angles near 90°, obtaining resolutions down to 22 km/pixel. Within a few hours of these observations, planetary rotation had moved the imaged territory into night, when the SSI observed it again. Images of lightning were obtained with resolutions down to 23 km/pixel. During all of these E11 observations, the spacecraft ranged from ~16 to 19 jovian radii from the planet’s center.

The areas covered by our C10 and E11 observations are shown in Figs. 1 and 2, respectively. The area surveyed corresponds to more than half the surface area of the planet. Unless otherwise noted, all latitudes in this paper are planetocentric, and all longitudes are System III west longitudes. Since the most important papers on Voyager lightning used planetographic latitudes, we give those latitudes in parentheses when comparing our results with theirs.

FIG. 1. Area surveyed during the C10 orbit. Here and throughout this paper we use planetocentric latitudes and west longitudes. The areas surveyed for lightning are white, while all other areas are gray. The 20 diamond symbols mark the positions of Storms 1–20 (Table I).
Jovian lightning occurs in clusters, which we call storms. Most storms exhibit multiple flashes within our images, and the storms are usually separated by large distances (~10^4 km). Table I is a complete inventory of the storms seen in C10 and E11. The C10 storms are numbered from 1 through 20, starting at the highest northern latitude and continuing south. The E11 storms are numbered in the same way from 21 through 26. The central latitudes and longitudes of the storms are given in the second and third columns, and these positions are displayed as diamond symbols in Figs. 1 and 2. The fourth column identifies the images in which each storm was seen, and for a given storm the images are listed in chronological order. Images that contain more than one storm are listed more than once. When a storm appears in more than one image, the latitude and longitude cited are the means of those quantities as evaluated separately for each image. The line and sample numbers in columns 5 and 6 give the central location of each storm in each image.

Column 7 of Table I gives the filter used in each image. CLR stands for the clear filter, which spans the range from 385 to 935 nm. RED spans 625 to 705 nm, GRN (green) spans 520 to 600 nm, and VLT (violet) spans 385 to 430 nm. All of these wavelength ranges are approximate, and do not include the small transmissions on the wings of the filter passbands. For a more complete discussion of the SSI’s properties, see Klaasen et al. (1997).

The first and second numbers in column 8 of Table I give each image’s exposure and gain state, respectively. The exposure is simply the time that the shutter was open, cited here in seconds. Since each lightning flash lasts much less than a second, and since storms generally have many flashes per minute, the longer exposures in Table I usually recorded many flashes per storm. The gain state (GS), represented in Table I by an integer between 1 and 4, describes the camera’s sensitivity. For gain states 4, 3, 2, and 1 the gain state ratio (which is inversely proportional to the sensitivity) is 1.0, 4.824, 9.771, and 47.135, respectively (Klaasen et al. 1997).

The last entry in column 8 of Table I gives the camera mode of each image, denoted by S for HIS mode or M for HIM mode. The former involves 2 × 2 summation, in which the data numbers (DNs), from neighboring sets of four adjacent pixels are summed before being stored on the tape recorder and then transmitted to Earth. The spatial resolution of this mode is intrinsically two times lower than that of HIM, and summed HIS pixels are two times wider than the point spread function (PSF) of the optical system. On the other hand, HIS mode is five times more sensitive than HIM (a factor of 4 due to the summing of 4 pixels, and an additional 25% due to a slight change in the sampling of analog signals from the detector). Using HIS allowed us to cover a larger fraction of the planet than would have been possible with HIM, since the number of pixels that could be transmitted to Earth was limited.

Light from just outside the field of view can get into the camera, and is often scattered onto the detector. Most of the scattered light in our images came from the twilight arc above Jupiter’s limb in C10 and from the planet’s sunlit crescent in E11. Such “off-axis” scattering adds a diffuse background to the SSI images, and can lead to saturation for long exposures and high-gain states. Since saturation means a complete loss of information above the maximum DN, our goal was to expose the background to one-half the maximum DN. The viewing geometry produced more scattered light in E11 than in C10, so our exposure times were generally shorter in E11.

Several frames are special. For example, image s0416080300, which captured Storms 7, 8, and 10, is a “scanned” frame. While the shutter was open, this frame’s footprint was deliberately scanned westward through an angle equivalent to 88 HIS pixels. This helped separate individual flashes within each storm, distributing them along a horizontal line. That in turn made it possible to measure the storms’ flash rates as well as the optical energy per flash. Image s0420783268, which does not appear in Table I, shows the appearance of Storm 24 on Jupiter’s day side 1 h 50 min before the two nightside images of this storm. Such dayside images allowed us to identify the cloud features associated with lightning.

Spacecraft attitude introduces a nominal pointing uncertainty of about 20 HIS pixels (40 HIM pixels). This uncertainty can be reduced to ≤1 pixel if the image contains a significant portion of the planetary limb or if stars are visible above the limb (Vasavada et al. 1998, Ingersoll et al. 1998). Since our data largely avoid the limb, we were forced to use the nominal pointing information supplied by the navigation team. To obtain a rough estimate of the pointing error in kilometers for a given image, its resolution (last entry in column 9 of Table I) should be multiplied by 20 for HIS mode or 40 for HIM. The resultant distance estimates are in the image plane, and can therefore be further corrected for the emission angle of the observation. For example, lightning at 47.5° latitude on the central meridian in an E11 image with 26 km/pixel resolution would be associated with a pointing error of 20 pixels × 26 km/cos 47.5° = 770 km = 0.6° latitude.
<table>
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<th>Lat.</th>
<th>Long.</th>
<th>Image Line</th>
<th>Sample</th>
<th>Filter</th>
<th>Exprs/GS/mode</th>
<th>EW × NS/Resolution (km)</th>
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<td>CLR</td>
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<td>534 × 599/134</td>
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<td>334 × 739/67</td>
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<td>319</td>
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<td>709 × 1129/133</td>
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<td>1239 × 870/133</td>
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<td>816 × 539/133</td>
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<td>74.5</td>
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<td>89.6/1/S</td>
<td>1256 × 539/133</td>
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<td>98.2</td>
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<td>51.2/4/M</td>
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<td>220 × 294/27</td>
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<td>507 × 117/27</td>
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<td>168.0</td>
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<td>105</td>
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</table>

Note. The six asterisks refer to the scanned frame, whose motion made it difficult to provide meaningful entries for the associated categories. The asterisks are mere placeholders in lieu of useful numbers.
3. APPEARANCE AND SIZE

Figures 3, 4, 5, and 6 each present illustrative images of lightning storms. Figure 3 contains Storms 7, 8, and 10 in its left panel image (s0416083400), and Storms 5, 11, 13, and 15 in its right panel image (s0416090800). Clouds are visible throughout these nightside frames because they were being illuminated by light from Jupiter’s moon Io. When that moon is full, the ratio of moonshine on the night side to sunshine on the day side is \( p(r_{Io}/R_{Io})^2 \), where \( p \) is the geometric albedo of Io, \( r_{Io} \) is Io’s radius, and \( R_{Io} \) is the distance from Io to Jupiter’s clouds. For \( p = 0.7 \), this ratio is \( 1.9 \times 10^{-5} \) — large enough to make the clouds visible on these long exposures.

Figure 4 shows three separate storms at two different times. The two left panels show Storm 11, the two middle panels show Storm 13, and the two right panels show Storm 15. The three top panels come from image s0416090600, while the three bottom panels come from image s0416090800, which was taken 2 min later. Since the location of individual flashes differed between these two images, the detailed appearance of each storm differs between the top and bottom panels. In addition to lightning, one can also see artifacts of the data compression in these images, particularly in the top and bottom middle panels and in the bottom left panel. These artifacts appear as little checkerboard squares, each \( 8 \times 8 \) HIS pixels.

The arrows in Fig. 5 point to Storm 26 (the patch at lower right) and Storm 23 (the much fainter patch at lower left). The resolution is 26 km/pixel, and the exposure is 6.4 s. At least partly because this resolution is 5 times better and the exposure is 7–14 times shorter than in Figs. 3 and 4, these storms look different from those in Figs. 3 and 4. Storms 23 and 26 have a single maximum and a well-resolved skirt, whereas the storms in Figs. 3 and 4 have many maxima and narrow skirts. One possible explanation of this difference is that Storms 23 and 26 represent single flashes. In fact, it is often difficult to distinguish single flashes from other features (see below), and for this reason we excluded images with exposures shorter than 6.4 s when constructing our inventory of storms.
A number of phenomena could potentially be mistaken for lightning. Those associated with Jupiter include auroras, satellite fluxtube footprints (FTFs), and meteors. Those associated with the camera include hot pixels and cosmic ray hits. We nevertheless feel reasonably confident that Table I lists all salient lightning in the C10 and E11 nightside images and does not list phenomena wrongly identified as lightning.

The easiest cases are the 16 storms that were imaged in multiple frames, since each storm’s overall location remained constant from frame to frame while the positions of its individual flashes changed slightly. The hardest cases are storms imaged only once at high latitudes, where lightning can be confused with auroral features. The main auroral oval is not a problem (e.g., Fig. 5), but small irregular patches are more difficult (e.g., frame s0420481445, which is not in Table I).

Satellite FTFs occur at predictable latitudes and longitudes, but caused some initial confusion with Storms 23 and 26 (Fig. 5). We realized that the two spots in Fig. 5 were lightning as we
learned to recognize the Io FTF from its appearance in other images. Similarly, Storm 21 was initially identified as the Europa FTF in frame s0420824600, but it reappeared in frame s0420829145 when the Europa FTF was far away. Hot pixels do not change their line-sample locations, and we were able to identify most of them by comparing frames s0416073300 and s0416083522. Cosmic ray hits have a characteristic appearance, either a short tapered line or an isolated spot with no skirt. Lightning, on the other hand, tends to have a skirt. Meteors are generally so small that any of them within our images would probably have been rejected along with cosmic ray hits. For example, Cook and Duxbury (1981) reported a 75-km-long streak in a Voyager 1 image that might have been a large meteor, but our lightning storms are all larger than this (Table I).

The last column of Table I lists the storm “type.” This is a subjective classification, based entirely on a storm’s appearance in an individual image. Type 1 storms are the largest, and are elongated in the east–west direction. They contain multiple flashes, and are invariably associated with long exposures. Type 2 storms appear smaller, although they also contain multiple flashes. Type 3 storms are smaller still, each usually appearing as a single ellipse. Type 4 storms are the smallest and faintest of all, always appearing as single ellipses. As Table I shows, some storms appeared to change type (e.g., Storm 19). Thus a given storm’s type classification probably depends on the camera settings and the vagaries of individual flashes, as well as on the storm’s real properties.

A “d” in Table I after the type number indicates that the storm appears to be a “double.” Some doubles may just be two flashes separated in position, and indeed most “d” storms do not appear double in all of their images (e.g., Storm 19). On the other hand, Storm 10 appears double in both of its staring (i.e., nonscanned) frames, and each component appears to contain multiple flashes. Thus it could be two closely spaced storms. The latitude, longitude, line, sample, and size given in Table I for a “d”-type storm refer only to the larger member of the pair. A typical separation between the two components is hundreds of kilometers.

The maximum east–west (EW) and north–south (NS) dimensions of our storms are given in the next-to-last column of Table I. Several steps went into these estimates. First, the dimensions in the image plane were determined by counting pixels and multiplying those numbers by the resolution in kilometers. Then these dimensions were increased by the appropriate foreshortening factors: secant latitude for the EW dimension and secant Δlongitude for the NS dimension, where Δlongitude was measured from the subspacecraft meridian. These foreshortening factors are valid approximations because the spacecraft was in the equatorial plane more than 15 jovian radii from the planet. Finally, the EW dimension of each Type 1 storm was reduced by the distance the storm had traveled due to planetary rotation during its exposure. Since the rotational speed is 12.5 km s⁻¹ at the equator, this was sometimes a substantial correction for our longest exposures (179.2 s).

The rationale for applying the rotational correction to Type 1 storms is that they contain multiple flashes. If a storm flashes repeatedly during an exposure, then it can be regarded as a steady light source whose EW dimension will appear larger than it really is by the EW distance the storm has moved during that exposure. On the other hand, if a storm supplies just two flashes during a long exposure, then its apparent EW dimension will depend exactly on when and where those flashes occur. Obviously, the apparent size of a storm that flashes only once during an exposure is unaffected by planetary rotation.

We also applied our rotational correction to Storms 1, 5 (second frame), 16, and 24 (second frame), all of which are Type 2. Here the rationale is less clear. Without the correction, the EW dimension of each storm was greater than 1000 km, which was larger than some of our Type 1 storms. Also, the correction did not make the EW dimension negative, as it did for many (~25%) of our Type 2 and Type 3 storms. When a rotational correction made this dimension negative, we concluded that the storm had not been flashing repeatedly during the exposure and thus could not be treated as a steady light source.

The final size estimates of Table I range from 99 to 1695 km. The largest storms are almost three times larger than those seen by Voyager, though Table I’s estimates must be viewed with caution for several reasons. First, it was not always clear where one storm ended and another began (e.g., Storm 7 vs Storm 8, Storm 19 vs Storm 20, or Storm 23 vs Storm 26). Second, apparent size can be a strong function of the camera settings (e.g., longer exposures will tend to capture more events over a wider area). And third, we are not dealing with immutable objects. A few large flashes can change the appearance of a storm considerably, and the statistics of these random events add a large (factor of 2) uncertainty to our size estimates. This effect is clearly more important for our shorter exposures.

4. RELATION TO CLOUDS AND WINDS

During E11 several places on the planet were tracked across the terminator from the day side to the night side—a time interval of 1 h 50 min. One of these sequences captured Storm 24. The corresponding images are shown in Fig. 6. The dayside image on the left (s0420783268) was taken through the 727-nm filter. This filter spans a weak absorption band of methane and detects aerosols down to the 4.0-bar range (Banfield et al. 1998). The two nightside images on the right in Fig. 6 show the same latitudes and longitudes as the white square in the dayside image, but they have been magnified by a factor of 2 to permit a better view of the lightning. The upper right panel is part of an image taken with a 166.9-s exposure through the RED filter in GS1 (s0420793801). The lower right panel is part of a 38.9-s RED in GS2 (s0420794201). The shutter opened on the latter nightside image 3 min 38 s after it opened on the first. The lower gain state and ~4.3 times longer exposure of the upper panel image has several effects: This frame recorded more lightning flashes, they appear more spread out in the east–west direction, and the
GALILEO IMAGES OF LIGHTNING ON JUPITER

FIG. 6. Dayside and nightside views of a lightning storm. The large panel on the left is an image of Jupiter’s day side (frame s0420783268), with the relevant latitudes and longitudes indicated along its axes. The two panels on the right show the area within the white box (upper left of the dayside image) 1 h 50 min later on Jupiter’s night side. Although the two right panels correspond exactly to the geography of the white box, they have been enlarged by a factor of 2 to permit a better view of their contents. Each contains an image of Storm 24. The top panel is a portion of frame s0420793801, and the bottom panel is a portion of frame s0420794201. These two nightside images were taken 3 min 38 s apart. The bright spot in the dayside box corresponds to a cloud that is optically thicker and perhaps 15 km higher than its surroundings.

The frame’s signal-to-noise ratio is lower. The larger EW spread is due mainly to planetary rotation. For a 166.9-s exposure at 48.5° latitude, the corresponding rotational motion is 1378 km (1.67° longitude).

It is difficult to correlate nightside lightning with dayside features imaged 1 h 50 min earlier because of the 20-pixel camera pointing uncertainty (~540 km or 0.65° longitude), smearing due to planetary rotation while the shutter was open, and physical motion due to zonal winds. Yet the correlation between lightning and the bright cloud within the dayside box of Fig. 6 is quite good. The fact that the lightning seems to line up best with a dark patch immediately west of the white cloud may be significant. This patch resembles a similar patch next to a bright cloud northwest of the Great Red Spot (Banfield et al. 1998). The latter cloud and patch were imaged through four filters during Galileo’s first (so-called G1) orbit. The use of multiple wavelengths allowed the authors to conclude that the bright cloud is both optically thicker and ~15 km higher than its surroundings, suggesting that the same is true of the bright cloud in Fig. 6. The neighboring patch in the G1 image looks dark in the weak methane filter (727 nm), but it looks bright in the continuum filter (756 nm). Banfield et al. concluded that this patch corresponds to a cloud at a depth greater than 4 bar and that it must be a water cloud. Water clouds are of course exactly where one might expect to find lightning.

Isolated bright clouds like the one in the dayside image of Fig. 6 often appear in the movies made from Voyager images (Avis and Collins 1983) [these movies are available as video AVC 9012T1SM Voyager Science Summary from Digital Generation Systems, 10545 Burbank Blvd., North Hollywood, CA 91601, (818) 753–3000]. Such clouds appear suddenly as bright white spots; they then expand rapidly, and are pulled apart in a few days by the surrounding shear flow. These spots almost always occur in cyclonic shear zones, within which rotation is clockwise in the southern hemisphere and counterclockwise in the north. A good example is the spot imaged in G1 northwest of the Great Red Spot. Such spots illustrate the disturbed nature of cyclonic regions relative to anticyclonic ones (Mac Low and Ingersoll 1986).

Figure 7 compares the latitudes of the 26 storms (Table I) with Jupiter’s zonal winds (Lima 1986). The displayed wind profile was derived from 1979 data, though less complete data taken with the Hubble Space Telescope in 1995 show that the zonal wind profile was not significantly different at that time (A. Simon, personal communication). As explained in the caption to Fig. 7, most of the 26 storms occur in cyclonic shear...
zones. Indeed, the only exceptions are the storms between 40° and 50° north, which seem to be clustered near the center of westward jets. There are 11 storms near the jet at 47.5° and one storm near the jet at 41.2°.

The lesson from Fig. 7 seems to be that lightning occurs either in cyclonic shear zones or near the centers of westward jets. The former are the most disturbed regions in the Voyager movies, exhibiting small convective storms. The latter are where the absolute vorticity gradient changes sign, and are thus the most unstable regions according to the barotropic stability criterion (Ingersoll et al. 1981, Limaye 1986). However, there are three caveats. First, the camera pointing uncertainty is a significant fraction of the ~5° zonal jet width (that uncertainty is roughly 20 pixels × 133 km/cos 47° = 3900 km = 2.9° latitude for most C10 images, and 20 pixels × 26 km/cos 47° = 762 km = 0.6° latitude for our E11 images). Second, the zonal wind profile might have changed between the 1979 measurements shown in Fig. 7 and our 1997 observations. Third, there may be a visibility effect, whereby lightning is effectively obscured by overlying clouds and hazes within anticyclonic shear zones and/or eastward jets (e.g., West et al. 1986). Nevertheless, it seems likely that lightning does not occur at random across the jovian disk. Possible implications for the dynamics are discussed in Section 7.

Incidentally, both viewing geometry and the density distribution of stratospheric aerosols render obscuration by overlying material especially plausible near the poles. This may be at least part of the reason why we did not detect any lightning poleward of ~56° latitude.

The right side of Fig. 7 is a histogram that shows the number of observed storms per unit area surveyed. The data are grouped into bins 5° wide, centered at latitudes 57.5°, 52.5°, 47.5°, etc. The numbers plotted also appear in column 4 of Table II. The width and centering of the bins are somewhat arbitrary, but 5° coincides roughly with the width of the jets, and is approximately two times greater than our most frequent pointing uncertainty. The centering we have chosen has the effect that bins with storms are often surrounded by empty bins. In constructing this histogram, all of the storms in Table I were treated equally—no attempt was made to take account of the storms’ relative size, intensity, or duration.

Table II presents various data for the 10 nonempty bins in Fig. 7. The first column gives the central latitude of each bin, the second column gives the number of storms observed in each bin, and the third column gives the area surveyed in each bin. The surveyed areas were taken from Figs. 1 and 2, and the E11 areas were simply added to those from C10. Thus the area surveyed within a given bin could sometimes be greater than the actual area on Jupiter in that bin. Our underlying assumption was that storms lasted for the duration of observations in a single orbit (up to ~2 days), but not for the 31 days between C10 and E11. Thus the survey received a fresh start in E11, and the area then

**TABLE II**

<table>
<thead>
<tr>
<th>Central latitude (deg)</th>
<th>Number of storms</th>
<th>Area (10⁹ km²)</th>
<th>Number/area (10⁻⁹ km⁻²)</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>57.5</td>
<td>2</td>
<td>1.02</td>
<td>1.96</td>
<td>5.0 × 10⁻⁶</td>
</tr>
<tr>
<td>52.5</td>
<td>1</td>
<td>2.03</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>47.5</td>
<td>11</td>
<td>2.62</td>
<td>4.19</td>
<td></td>
</tr>
<tr>
<td>42.5</td>
<td>1</td>
<td>2.38</td>
<td>0.42</td>
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</tr>
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<td>2</td>
<td>1.47</td>
<td>1.36</td>
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</tr>
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<td>2</td>
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<td>1.33</td>
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</tr>
<tr>
<td>7.5</td>
<td>2</td>
<td>1.58</td>
<td>1.27</td>
<td></td>
</tr>
<tr>
<td>−32.5</td>
<td>1</td>
<td>1.34</td>
<td>0.74</td>
<td></td>
</tr>
<tr>
<td>−42.5</td>
<td>1</td>
<td>1.40</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td>−52.5</td>
<td>3</td>
<td>0.45</td>
<td>6.68</td>
<td>0.251</td>
</tr>
<tr>
<td>Total</td>
<td>26</td>
<td>39.5°</td>
<td>0.66°</td>
<td></td>
</tr>
</tbody>
</table>

* Total area surveyed, including bins that did not contain lightning.
Galileo Images of Lightning on Jupiter

The bottom row of Table II ("Total") gives in its second column, the total number of storms, and in its third column, the sum of all areas surveyed. Since the latter includes bins that did not contain lightning, the total area in the bottom row is greater than the sum of the areas above it in the same column. The fourth column of Table II and the histogram bars in Fig. 7 are just the second column divided by the third column. The fourth column of Table II and the histogram bars in row is greater than the sum of the areas above it in the same bins that did not contain lightning, the total area in the bottom column, the sum of all areas surveyed. Since the latter includes "new." The bottom row of Table II gives the number of storms per unit area (6.68 x 10^9 km^-2) because it contains three storms and its surveyed area is small. This number is 10 times larger than our average for the entire survey, namely, 0.66 x 10^-9 km^-2 (fourth column, bottom row). The 47.5° bin has 11 storms, but the corresponding area surveyed is so large that the number of storms per unit area is 4.19 x 10^-9 km^-2. These 11 storms occur between the latitudes of 46.6° and 49.0°, which is slightly north of Voyager’s main lightning band at 45° (49° planetographic). Figure 7 shows that the Voyager lightning band was a cyclonic shear zone at the time the storms were observed. Our data show that this active lightning band was still present in 1997, but it had moved northward relative to its position in 1979 by ~2.5°.

The last column of Table II gives the probability that the observed number of storms could have occurred by chance. To estimate these probabilities, we used both a Monte-Carlo method and an analytic approximation. The analytic approximation is an extension of the standard binomial distribution. The latter gives the probability of putting n objects (the 26 storms) into a box (the total area surveyed) and having m of those objects fall within a smaller box (one of our latitude bins) that occupies a fraction f of the total area. The extension is necessary because there is nothing special about any particular bin. In our problem there are 1/f identical latitude bins, and we want the probability P(m) that any one of them will have m objects. If the probabilities are very low, the chance of more than one bin having m objects during one realization is negligible. Then the bins will not interact, and we can simply multiply the standard binomial formula by the number of bins (1/f). Thus

\[ P(m) = (1/f)^m (1 - f)^{n-m} m^n / (n-m)! \]  

The above formula is inaccurate for \( P(m) > 0.1 \), so we used the Monte-Carlo method for the -52.5° bin. The Monte-Carlo method agrees with (1) when \( P(m) \) is 10^-3 to 10^-4, but for smaller values the Monte-Carlo method is subject to statistical fluctuations. This is where Eq. (1) is most accurate, so we used it for the 47.5° bin. The final step is to sum over all \( P(m) \) for \( m \) greater than or equal to the observed number (second column of Table II). The result (column 5 of Table II) is the probability of at least the observed number of storms falling in a bin of that size.

The table gives only the two smallest probabilities (5.0 x 10^-6 for the 47.5° bin and 0.251 for the -52.5° bin). Although the numbers for the other bins are not statistically significant when regarded individually, collectively they indicate a preference for cyclonic regions. The exceedingly small probability associated with the clustering at 47.5° demonstrates that there is something special about that latitude, as pointed out by Borucki and Magalhães (1992). There is probably also something special about ~52.5°, though that is less obvious from Table II.

As with Voyager, we observed considerably less lightning in the southern hemisphere. Voyager observed none, and only 5 of our 26 storms are in the south. Moreover, the two storms between the equator and -49° (Storms 16 and 17) appear small and weak relative to the six storms between the equator and +41° (Storms 10–15). We found less lightning in the south partly because we surveyed less area there, but a comparison of equal northern and southern C10 areas suggests that the south really does have substantially less visible lightning.

Patterns in the longitudinal distribution of lightning are harder to detect than patterns in the latitudinal distribution. Figures 1 and 2 are inconclusive with respect to longitudinal patterns, although more observations and better statistics would help. Similarly, our data do not allow any estimate of the longitudinal motions of storms, since the longest interval between our images of the same storm is ~1 h. Any longitudinal drift during this interval would likely have been less than the uncertainty in our camera pointing.

The Great Red Spot (GRS) is centered at ~20° latitude. During the C10 orbit (Fig. 1), its east and west ends were at 78° and 97° longitudes, respectively. Frame s0416098400, which imaged Storms 16, 18, and 19 (Table I), also imaged the eastern half of the GRS. If there had been significant lightning activity in that vicinity when this frame was taken, it should have shown up in this image. However, none was seen. Our data are thus consistent with the idea that the GRS itself contains little or no lightning. Any disturbance northwest of the GRS like the one seen during the G1 orbit (Banfield et al. 1998) would have been just outside our field of view.

The three white ovals BC, DE, and FA are centered at ~30° latitude. During C10 their east and west ends were at longitudes 58° and 66° (BC), 76° and 85° (DE), and 98° and 104° (FA). Thus these ovals were also covered in our survey (Fig. 1). Storm 16 (latitude = ~34.5°, longitude = 74.5°) occurred just southeast of the DE oval, but we cannot be sure if this was due to a physical connection or mere coincidence.

5. Energy, Power, Color, and Flash Rate

The optical energy of any lightning flash in our images can be estimated from “DN Sum,” which is the sum of data numbers over all of the pixels in the flash. In doing this sum, one must subtract off the background DN level, which is estimated from the pixels surrounding the flash. Data compression introduces a quantization error to our estimates of DN Sum (K. Klaasen, private communication). However, this error is statistical in nature and does not introduce a systematic bias, so we have ignored it.
We used the calibrations of Klaasen et al. (1997) to convert DN Sum into intensity. We treated each flash as a patch of light on a Lambert surface, so that the upward flux was assumed to be \(\pi\) times the intensity (i.e., the upward irradiance was assumed to be \(\pi\) times the radiance). On the assumption that there was an equal downward flux, we set the total optical power to \(2\pi\) times the intensity times the horizontal area of the emitting patch. That horizontal area is \(\sec(e)\) times the area in the image plane, where \(e\) is the emission angle.

The result is probably only a lower bound on the emitted optical energy, since the light we saw at the tops of the clouds had diffused upward through a scattering medium. In this process, most (up to 90%) of the light may have been absorbed or reflected back downward, as the average optical thickness of the clouds is \(\sim 5–10\) (Banfield et al. 1998). Ignoring these possibilities, we use the following expression for the energy:

\[
\text{Energy} = (\text{DN Sum})(\text{Pixel Area})[2\pi \sec(e)](\Delta \lambda)/(10^3 \, S). \tag{2}
\]

The equation resembles Eq. (8) of Ingersoll et al. (1998), although there are differences. In both cases, Pixel Area is the square of the pixel size in the image plane (133 \(\times\) 10\(^5\) cm for the scanned frame), \(\Delta \lambda\) is the width of the relevant filter (550 nm for CLR), and \(S\) is the camera sensitivity for the relevant filter, mode, and gain state (8.55 \(\times\) 10\(^7\) DN ms\(^{-1}\) W\(^{-1}\) cm\(^{-2}\) sr nm for HIS CLR in GS2; see the column labeled Earth-2 in Table 3 of Klaasen et al. 1997). However, since Ingersoll et al. assumed that their emitter (the jovian aurora) was optically thin, they used 4\(\pi\) steradians instead of 2\(\pi\) \(\sec(e)\). Also, because Ingersoll et al. were computing the power of a steady source, they had to divide by the exposure time. In Eq. (2) we are computing the energy of a single event, so we do not divide by the exposure time. Because the camera sensitivity uses ms for the exposure time and W for power, the answer comes out in ms-W, or mJ. Converting to J involves multiplying by the number of J/mJ, hence the factor of 10\(^3\) in the denominator of Eq. (2).

Applying Eq. (2) to the scanned frame (s0416080300), we can derive a histogram of the energy of individual flashes for Storms 7, 8, and 10. During that frame’s 59.8-s exposure (Table I), the field of view was panned from east to west a distance equivalent to 88 HIS pixels across the scene. Each storm left a trail of spots—flashes—aligned in the scan direction. The linearity of the pattern allowed us to identify weak flashes that otherwise would be indistinguishable from cosmic ray hits. However, it is difficult to distinguish the flashes of Storm 7 from those of Storm 8 because of the loss of position information caused by the scanning motion. Storms 7 and 8 together had a combined total of 18 identifiable flashes, and Storm 10 also had 18 identifiable flashes. The smallest observed flashes are at the detection threshold of the camera, and there may have been flashes below this threshold. Both the brightness and spacing of the observed flashes are irregular.

The result of applying Eq. (2) to those flashes is given in Table III and Fig. 8. For each group (Storms 7 and 8 are grouped together), we have numbered the flashes from \(N = 1\) to \(N = 18\) in order of decreasing energy \(E\). Figure 8 plots \(N(E)\), the cumulative frequency distribution. The bottom row of Table III gives the sums of the table’s third and fifth columns, i.e., the energy of all the flashes observed during the 59.8-s exposure. Note that in each column the 3 largest flashes (out of 18) contain more than half of the column’s total energy.

The largest individual flash seen by Galileo is 15.7 \(\times\) 10\(^9\) J, which is about 2.5 times the largest flash seen by Voyager 1, though not as large as most of the spots seen by Voyager 2. Since Voyager 2 had much poorer spatial resolution than Voyager 1, Borucki and Magalhaes (1992) suggest that the Voyager 2 events were the “culmination of many flashes within large storms rather than individual flashes.” The largest terrestrial flashes, termed superbolts (Table II of Borucki et al. 1982), are three times smaller than the largest flash seen by Galileo.

Storms 7, 8, and 10 appeared in two other CLR images besides the scanned frame (Table I), and it is interesting to compare these three images for their estimates of the storms’ average optical power. The standard deviation among these estimates for a given storm provides information about large, rare flashes, since they carry most of the energy and therefore account for most of the observed variance. Moreover, any systematic difference between the scanned frame and the two staring frames would provide information about small flashes that might have escaped detection in the scanned frame, but which would still have contributed to the total energy measured in the staring frames.

Results are given in Table IV. The fourth column gives each frame’s spacecraft event time in hh:mm:ss on October 5, 1997, and shows that all the images of Storms 7, 8, and 10 were taken
FIG. 8. Cumulative distribution of the optical energy in individual flashes. The abscissa is the energy $E$ in Joules associated with individual flashes from the scanned frame, s0416080300. The upper set of points (open circles) represents the 18 flashes from Storms 7 and 8, and the lower set (filled circles) represents the 18 flashes from Storm 10. The ordinate is the number of the flash from $N = 1$ to $N = 18$, in order of decreasing energy. These data are also recorded in Table III. To improve the display, we have shifted the points for Storms 7 and 8 upward by a factor of 10.

TABLE IV

<table>
<thead>
<tr>
<th>Image</th>
<th>Filter</th>
<th>Width (nm)</th>
<th>SCET (10/5/97)</th>
<th>Power ($10^9$ W)</th>
<th>Spectral density ($10^5$ W/nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storms 7 and 8</td>
<td>CLR</td>
<td>385–935</td>
<td>22:26:50</td>
<td>0.494</td>
<td>0.898</td>
</tr>
<tr>
<td>s0416079900</td>
<td>CLR</td>
<td>385–935</td>
<td>22:30:53</td>
<td>0.622$^a$</td>
<td>1.131$^a$</td>
</tr>
<tr>
<td>s0416083400</td>
<td>CLR</td>
<td>385–935</td>
<td>23:02:14</td>
<td>0.905</td>
<td>1.645</td>
</tr>
<tr>
<td>s0416081400</td>
<td>GRN</td>
<td>520–600</td>
<td>22:42:00</td>
<td>0.047</td>
<td>0.588</td>
</tr>
<tr>
<td>s0416081768</td>
<td>RED</td>
<td>625–705</td>
<td>22:45:48</td>
<td>0.311</td>
<td>3.888</td>
</tr>
<tr>
<td>s0416082145</td>
<td>VLT</td>
<td>385–430</td>
<td>22:49:35</td>
<td>0.099</td>
<td>2.200</td>
</tr>
<tr>
<td>Storm 10</td>
<td>CLR</td>
<td>385–935</td>
<td>22:26:50</td>
<td>0.292</td>
<td>0.531</td>
</tr>
<tr>
<td>s0416079900</td>
<td>CLR</td>
<td>385–935</td>
<td>22:30:53</td>
<td>0.972$^a$</td>
<td>1.767$^a$</td>
</tr>
<tr>
<td>s0416083400</td>
<td>CLR</td>
<td>385–935</td>
<td>23:02:14</td>
<td>0.798</td>
<td>1.451</td>
</tr>
</tbody>
</table>

$^a$ Scanned frame.

within a 35-min interval. The fifth column gives the average optical power, which is simply the measured energy divided by the exposure time. For each nonscanned frame, the energy was evaluated over the entire storm area rather than over individual strikes. The dominant feature of the resultant power estimates is the large (factor of 3) variation for the same storm as it appeared through the CLR filter at different times. This is consistent with the data in Table III, which show that in a 59.8-s exposure the three largest flashes carry more than half the total energy. The statistics of these relatively rare events thus explain the large differences among the three successive CLR images, whose exposure times were 44.8, 59.8, and 44.8 s, respectively.

For each of the storms, the power in the scanned frame is just as large as that in at least one other CLR staring frame. Thus the energy associated with subthreshold flashes is not a large part of these storms’ total energy. On the other hand, the $N(E)$ curves of Fig. 8 seem to be rising at the low-energy end, suggesting that there are additional flashes below the detection threshold. There could even have been more flashes below this threshold than above it, provided their total energy was not large compared with that in the observed flashes.

To estimate the planet’s optical power per unit area, we take the average power per storm, and multiply by the number of storms per unit area. The average of the three CLR filter power estimates is $0.674 \times 10^9$ W for Storms 7 and 8 together and $0.687 \times 10^9$ W for Storm 10. Since there are three storms, the average optical power per storm is $0.454 \times 10^9$ W. There were 26 storms (Table I), and the total area surveyed was $39.5 \times 10^8$ km$^2$ (Table II). Thus the power per unit area is $0.30 \times 10^{-6}$ W m$^{-2}$. Using Voyager 1 data, Borucki et al. (1982) estimate $2.5 \pm 1.9 \times 10^9$ J per flash and an average rate of $4 \times 10^{-3}$ flashes km$^{-2}$ year$^{-1}$, which is equivalent to $0.32 \times 10^{-6}$ W m$^{-2}$. This agrees very well with the Galileo estimate. The Voyager 2 estimate is almost double that for Voyager 1 (Borucki and Magalhães 1992), but such differences are no larger than the statistical fluctuations seen in Table IV. Using Borucki and Chameides (1984), we find that the terrestrial rate is $0.4 \times 10^{-6}$ W m$^{-2}$ (a global dissipation rate of $4 \times 10^{10}$ W times an optical efficiency of 0.0054, divided
by Earth’s surface area). This is 1.3 times the Galileo estimate, although Earth’s total emitted power is ~100 times less than Jupiter’s because it is so much smaller.

The color of the lightning is difficult to quantify because our filtered images were taken at different times. Thus the individual flashes that they photographed were different. If a storm is flashing rapidly enough, however, we can treat it as a steady light source. The scanned frame (s0416080300) suggests that Storms 7 and 8 were flashing rapidly enough to have approximated steady light sources for our longest exposures. Both storms were imaged once each in RED, GRN, and VLT, as well as three times each in CLR.

Laboratory simulations have shown that Jupiter’s visible lighting spectrum is probably dominated by line and continuum radiation from atomic hydrogen and helium (Borucki et al. 1985, 1996). The first line Hα of the Balmer series of atomic hydrogen is always prominent, and falls within our RED filter. Although the second Balmer line Hβ (at 486 nm) falls outside the passbands of our narrow filters (between GRN and VLT), the VLT filter contains several other lines of the Balmer series. Our GRN filter contains the 587.6-nm line of helium, while our CLR filter includes all of the above lines. The relative importance of all these lines—and of continuum emission—depends on the depth at which the lightning occurs. As the ambient pressure is increased from 1 to 5 bar, the prominence of line radiation diminishes compared with continuum radiation, and the 587.6-nm helium line virtually disappears (cf. Figs. 1 and 2 of Borucki et al. 1996).

The data of Table IV provide coarse spectral information. In particular, the last column gives the spectral energy density, which is simply the previous column’s power in watts divided by the filter width in nanometers (see column 3). The spectral energy density is greatest in RED, where it is more than three times the average CLR value. The value for VLT is also greater than that for CLR, while the value for GRN is less than half the average CLR value. The RED and VLT emissions may be mostly Balmer lines, but Balmer lines are clearly not the whole story since none of them falls within the GRN passband. The spectral energy density in GRN is 15% that in RED, but our data cannot assess the relative contributions to GRN of the 587.6-nm helium line versus continuum emission versus other line emission.

The flash rate is defined as the number of flashes per unit area per unit time. A lower bound on this quantity can be obtained by taking the average of 12 observed flashes per storm in the scanned frame (36 flashes for 3 storms), multiplying by 26 storms (Table I), dividing by the 59.8-s exposure time (Table I), and then dividing by the total area surveyed (39.5 × 10² km², Table II). The result is 4.2 × 10⁻³ flash km⁻² year⁻¹. This agrees well with the estimate of 4 × 10⁻³ flash km⁻² year⁻¹ obtained from Voyager 1 images (Borucki et al. 1982), but is ~10⁻³ times the terrestrial rate of 6 flashes km⁻² year⁻¹ (Borucki and Chameides 1984, Uman 1987).

Terrestrial lightning and jovian lightning are thus similar in some respects—the energy in the largest flashes and the optical power per unit area—but they differ in others. Earth and Jupiter appear to differ in their global flash rates, but that could be due to the greater dynamic range of terrestrial lightning observations (10³ or more, according to Borucki and Chameides 1984) compared with that of Galileo (75, according to Table III). If Galileo’s scanned frame saw only the high-energy tail of the jovian lightning distribution, then even the global flash rates of the two planets might be similar.

6. DEPTH OF THE LIGHTNING

As pointed out by Borucki and Williams (1986), the apparent size of a lightning flash at the top of the jovian clouds is a measure of the depth of the light source. Deeper flashes appear wider because their light undergoes more scattering by intervening particles. Jupiter’s atmosphere is thought to contain three major cloud decks above the 8-bar level and two aerosol layers above these clouds. The upper cloud is composed of ammonia, the middle one probably consists mainly of ammonium hydrosulfide, and the lower cloud is thought to be water. Borucki and Williams found that Voyager 1’s flashes seem to originate at a depth of ~5 bar, and concluded that the lightning was occurring in the water cloud.

With resolutions of 67–134 km per pixel, C10’s images are probably too coarse to have resolved individual flashes. By contrast, E11’s resolution of 23–27 km per pixel is better than Voyager 1’s nominal resolution of 37 km per pixel (Borucki and Williams, 1986). Further, Galileo’s E11 images are in HIS (summation) mode, so its pixels are two times wider than the camera’s point spread function (Klaassen et al. 1997). Since Voyager’s pixels are comparable to its point spread function, Galileo’s advantage is actually greater than that suggested by the nominal spatial resolutions.

Figure 9 illustrates our depth analysis by presenting data from three E11 lightning patches that are both well resolved and well exposed. The spots in Figs. 9a and 9b appear to be the widest and second widest single E11 flashes, respectively, while the spot in the center of Fig. 9c seems to be one of the narrowest, well-exposed single E11 flashes. Of course, we cannot rule out the possibility that any given lightning patch is really two or more closely spaced flashes.

The upper panels of Figs. 9a, 9b, and 9c each show raw DNs in the image plane within and around the relevant spot. Note that Fig. 9 shows unprojected pixels, whereas Figs. 5 and 6 have been map-projected onto a rectangular latitude–longitude grid. The ellipses in the upper panels are the projections of horizontal circles of radii 60 km, 120 km, 180 km, etc., centered on the relevant spot’s central pixel. Since there is scattered light, the background DN is not zero. The energies of the central flashes in Fig. 9a (Storm 26), Fig. 9b (Storm 22), and Fig. 9c (Storm 24) are 1.56 × 10⁹, 0.34 × 10⁹, and 0.64 × 10⁹ J, respectively. These are somewhat smaller than the mean flash energies characterizing columns 3 and 5 of Table III (Storms 7, 8, and 10).
FIG. 9. Raw data numbers from Storms 26, 22, and 24. The three upper panels are maps in the image plane of raw data numbers (DNs) in and around three different lightning patches. (a) Storm 26 in its entirety. (b) The larger member of the pair of spots in Storm 22. (c) Second brightest spot (to the SW of the brightest spot) in the lower right panel of Fig. 6 (part of Storm 24). The elliptical curves are the projections of horizontal circles centered on each patch’s central pixel. To an observer directly above the event, these curves would look like concentric circles of radius 60 km, 120 km, 180 km, etc. The systematic deviation of the isophotes from these curves suggests that jovian flashes naturally look longer in the vertical direction (see text). The lower panel in each figure shows DNs above background for all pixels, plotted against their radial distance in the horizontal plane of Jupiter from the central pixel. These lower plots provide the half-width at half-maximum (HWHM) of each patch, which we have used to infer the depth of the corresponding strikes. In these lower plots, the central pixel is difficult to see because it is plotted on the vertical axis. Its DN values for (a), (b), and (c) are 152, 57, and 112, respectively. The noisy tail in (c) is due to overlap with a neighboring flash, which is visible in the upper right quadrant of the top panel of (c). This neighbor is the brightest flash in the lower right panel of Fig. 6.
On the simplest scattering models, a single flash would exhibit a smooth, monotonic falloff in brightness away from its center, and it would look circular as seen from directly overhead. The three examples in Fig. 9 show a smooth falloff in brightness, but they are not perfectly circular—the isophotes do not exactly follow the ellipses in Fig. 9’s upper panels. For example, the second ellipse from the center of Fig. 9a seems to cross higher DN values at top and bottom than at left and right. Indeed, for all of the E11 spots we have analyzed (including three not shown in Fig. 9), DN values always seem to be largest where the ellipse is narrowest—on opposite sides of the ellipse across its semiminor axis. We discuss two possible explanations.

The first possibility is that each spot represents multiple flashes rather than a single flash. On this hypothesis, one would expect to find at least two local maxima within each spot, contrary to what is observed (although our resolution is finite). One also expects on this hypothesis that among different flashes, the isophotes would bulge in random directions (i.e., along the randomly oriented straight lines joining the multiple flashes). However, we have found that the bulge of the isophotes is always along the narrow axis of the ellipse, which is the projection of the local vertical. This leads to a second, more plausible explanation, namely, that single flashes naturally look longer in the vertical direction. This elongation could be produced by a vertical orientation of the lightning, by the way its photons are scattered, by the spacecraft’s oblique line of sight, or by some combination of these effects. While it seems especially plausible that this regularity reflects lightning’s preference for a vertical geometry, we have not carried our models far enough to rule out other possibilities.

For bell-shaped intensity profiles such as those in the bottom panels of Fig. 9, the half-width at half-maximum (HWHM) is defined as the radius at which the brightness is one-half its peak (i.e., central) value. This quantity is \( \sim 80 \) km for Fig. 9a, \( \sim 70 \) km for Fig. 9b, and \( \sim 45 \) km for Fig. 9c. E11’s Type 4 storms seem to have HWHMs in the range \( \sim 50–65 \) km, although these storms are substantially dimmer and therefore harder to evaluate than the Type 2 and Type 3 storms shown in Fig. 9.

Borucki and Williams (1986) report that the average HWHM measured for flashes in the Voyager images is \( 55 \pm 15 \) km (2σ error), which is close to the Galileo values. However, the authors note that the brightness profile they measured is actually a convolution of the true brightness profile and the PSF of the Voyager camera. Their Fig. 5 shows estimates from a radiative transfer model of true brightness profiles for sources at various depths. Their Fig. 6 shows these profiles after convolution with the Voyager PSF. That figure’s curve labeled “Lightning at 5 bars” fits the measured HWHM of \( \sim 55 \) km. However, the true profile corresponding to that model has a HWHM of only 30 km, as shown in Borucki and Williams’ Fig. 5. This profile is significantly narrower than any flashes confidently identified in the Galileo E11 images.

The true profile is what one would see in a camera with perfect resolution. The E11 Galileo images are not perfect; they have \( \sim 25 \)-km resolution. But the effect of the PSF is negligible, and the flashes shown in Fig. 9 are well resolved. We experimented with synthetic profiles—a Gaussian and a cosine bell—sampled at the resolution of the E11 images. When the true HWHM is 70 km, the measured HWHM ranges from 71 to 73 km depending on where the center of brightness falls inside the central pixel. When the true HWHM is 40 km, the measured HWHM ranges from 41 to 45 km. Thus it is likely that our estimates of the HWHMs are close to the true values.

The Galileo estimates of the true HWHM of jovian lightning flashes are therefore significantly larger than the Voyager estimate. Reconciling these two data sets is beyond the scope of this paper. Instead, we use the Galileo HWHM values to estimate the depth of the lightning. Borucki and Williams did not consider sources deeper than 5 bar, so their model results are not directly applicable to the wider Galileo flashes. We offer two models whose extreme simplicity at least matches the large uncertainty in the scattering properties of the deep atmosphere. Assume that a typical photon escapes to space at the level where the optical depth \( \tau = 1.0 \). We thus define \( \beta \equiv d/HWHM \), where \( d \) is the vertical distance of a light source below the \( \tau = 1 \) level. The general idea is to use various models to derive \( \beta \) and then to infer the depth \( d \) from the measured HWHM.

Our first approach is to derive \( \beta \) for an analytically tractable problem, namely, a point source at depth \( d \) below a thin translucent screen (which includes the \( \tau = 1 \) level). The upward flux \( F(r) \) at the top of the screen is given by

\[
F(r) = F(0)/[1 + (r/d)^2]^{3/2},
\]

where \( r \) is horizontal distance from the vertical axis of symmetry. The HWHM is that radius \( r \) where \( F(r) = F(0)/2 \). According to Eq. (3), this is where \( \beta = d/HWHM = 1.3 \). In our second approach, we use a Monte-Carlo model that assumes conservative isotropic scattering in a homogeneous layer that extends from the \( \tau = 1 \) level down to a point source at optical depth \( \tau_0 \). The case \( \tau_0 = 8 \) gives \( \beta = 1.5 \). Increasing \( \tau_0 \) to 16 changes \( \beta \) to 1.6. For illustrative purposes we use \( \beta = 1.5 \). Note that this number is highly uncertain. For the Galileo HWHMs of 45, 70, and 80 km, \( \beta = 1.5 \) yields inferred depths \( d \) of 67.5, 105, and 120 km, respectively.

To get a sense of how large these depths are, particularly the latter ones, consider the vertical structure measured by the Galileo probe. The tops of the clouds are likely to be below the tropopause (West et al. 1986, Banfield et al. 1998), which is near the 0.1-bar level. For this region, Tables 7 and 8 of Seiff et al. (1998) give the \( (z, P, T) \) relationships shown in Table V, where \( z \) is the distance in kilometers above the 1-bar level, \( P \) is pressure in bar, and \( T \) is temperature in Kelvin. Table V shows that to obtain depths of 105 and 120 km below the cloudtops, one has to go down to the 5- to 8-bar region. For instance, the vertical distance between the 0.1358-bar level and the 8-bar level is 115 km. The data of Fig. 9a thus imply that, at least at one place on the planet, the lightning is below the 8-bar level, or the top scattering layer is above the 0.1358-bar level, or both.
Further insight is gained by estimating where the water cloud base would be for various amounts of water in the deep atmosphere. The atmosphere was not saturated at the Galileo probe site, but if it were, the mole fraction of water would have been equal to the ratio of the saturation vapor pressure of water to the total pressure. That ratio is given in the last column of Table V. The values relative to the “solar” water abundance ($1.7 \times 10^{-3}$ according to Fig. 6A of Niemann et al. 1998) range from 0.78 at the 5-bar level to 6.41 at the 8-bar level. These are the enrichment factors relative to “solar” that would be required if the water cloud base were at 5 and 8 bar, respectively. The enrichment factors for other condensable gases are around 3 (Niemann et al. 1998). Thus a sixfold enrichment for water is surprisingly large, and a cloud base at 8 bar is surprisingly deep.

It thus appears that our E11 flashes are originating within or below the water cloud. Of course, there are many uncertainties. The vertical extent of the water cloud is not well known. The flashes may be multiple. Even single flashes are not point sources, and may be elongated over many kilometers vertically and/or horizontally. Our estimate of $\beta$ is crude, and we may have used the wrong parameters in the scattering model. But the basic fact is that our estimates of the true widths of jovian lightning flashes range up to $\sim 2.5$ times those inferred from the Voyager images. This observation, by itself, is significant.

The results of this section are interesting in view of the fact that we have also been able to associate lightning with bright day-side clouds which seem to be much higher than the water cloud (cf. Fig. 6). It may be that these bright clouds are simply the surface signature of a deep process, having themselves been created by updrafts that originate at much lower levels. Indeed, jovian lightning may occur primarily inside the deep roots of such clouds (cf. Fig. 6 of Banfield et al. 1998).

### 7. DISCUSSION

Despite all our observations tell us, they nonetheless leave a number of interesting questions unanswered. For example, we know very little about the lifetime of jovian lightning storms. The longest interval between our images of the same storm is $\sim 1$ h, but clearly the storms could last much longer than that. It is even possible that some storms seen in C10 were still flashing 31 days later during our E11 observations. However, if jovian storms correspond to the sudden brightenings within cyclonic shear zones that appear in the Voyager movies, then they probably last only several days before being pulled apart by opposing currents.

Our estimates of the optical energies of jovian flashes are probably only lower bounds. Most of the emitted energy may be absorbed or scattered back down before some of it manages to escape from the tops of the clouds. Over most of the planet, the optical thickness of clouds at $P < 1$ bar is of order 5–10 (Banfield et al. 1998). This is so large that most photons from flashes occurring below this depth will not escape to space, unless through holes in the overlying clouds. A thorough analysis might attempt to model light attenuation as well as the lighting spectrum and to derive the total energy dissipated per flash. From this last quantity one could estimate the global energy dissipation rate, as well as the implied global production rate for trace gases and organic compounds.

Our color data were unable to determine whether or not jovian lightning involves appreciable continuum emission. More images in more color filters would help. Galileo is not in a position to perform such a role, partly because it is now near the end of its mission. Although the Cassini spacecraft will have a spatial resolution on Jupiter of 60 km per pixel at best, it will be able to take many more images than Galileo. Since this spatial resolution is adequate for color studies, Cassini has a significant role to play in resolving the remaining spectral ambiguities.

We have estimated energies and depths for a relatively small number of the flashes represented in Table I, and we have not yet looked for lightning in the C10 images with exposures $< 6.4$ s. A thorough analysis of the Galileo data is called for. For a number of questions, the scattering properties of the deep atmosphere are a major uncertainty. Although plane–parallel radiative transfer models are not suitable for lightning problems, Monte-Carlo methods should work.

The spatial distribution of the lightning is provocative. We have confirmed the Voyager observation that the latitude zone between 45° and 50° in the north has more lightning per unit area than is typical of the planet as a whole. The same seems to be true of the latitude zone from $-50^\circ$ to $-55^\circ$ in the south, and the incidence of lightning seems to exhibit a rough increase away from the equator toward $\sim 50^\circ$ latitude in both hemispheres. We do not fully understand these trends, though they may be partly due to an increased heat flux from the planetary interior at high latitudes (Ingersoll and Porco 1978, Pirraglia 1984). Our data, like Voyager’s, also suggest that the northern hemisphere generally has more lightning than the southern hemisphere. This asymmetry between hemispheres, like a number of other well-known ones visible in day-side images, has yet to be explained. Perhaps further modeling can help us understand these patterns. Meanwhile, Cassini observations should clarify the lightning’s true spatial distribution and provide a near-simultaneous determination of Jupiter’s zonal winds. Cassini might even be able to follow storms long enough to determine their life spans and to detect longitudinal motions and patterns among Jupiter’s storms.
The association of lightning with cyclonic regions is important because it is telling us about the mechanics of moist convection, which may be the dominant mode of vertical heat transfer on Jupiter. Although the association is not perfect, the only observed band of lightning that does not quite fit is the one between 40° and 50° latitudes. Cyclonic regions are the traditional “belts” of Jupiter (Ingersoll et al. 1981, Limaye 1986, Gierasch et al. 1986). They are also the most active regions in the Voyager movies. According to Voyager’s IRIS data (Flasar et al. 1981, Conrath et al. 1981, Gierasch et al. 1986), Jupiter’s belts are also warmer than the adjacent “zones,” at least in the upper troposphere (100–250 mbar).

The IRIS data have traditionally been interpreted as implying that vertical motion in the belts is downward. The argument is based on steady-state energy balance: The excess radiative cooling in the warmer belts is balanced by the downward advection of high-entropy air. There is less radiative cooling in the colder zones, where the flow is presumed to be upward. This interpretation is consistent with the observed excess 5-μm radiation in the belts, which suggests fewer clouds and more downwelling. However, lightning is probably associated with moist convection, which is thought to be triggered by the upward transport of moisture-laden air from Jupiter’s interior. Indeed, our dayside images strongly suggest the presence of localized updrafts near jovian lightning. Our lightning data therefore seem to imply that at least some of the vertical motion in the belts is upward.

How can the IRIS data be reconciled with our lightning data? Perhaps the belts have updrafts at the cloud base and downdrafts at the cloudtops where the IRIS temperatures were measured. Or perhaps localized updrafts, like those suggested by our dayside images and the Voyager movies, are embedded within large-scale downdrafts. Perhaps lightning in the belts does not require updrafts. Or perhaps energy balance in the belts does not require downdrafts. This last possibility represents a major shift in the traditional view of Jupiter’s belts and zones. For instance, it is possible that the belts are warmed by moist convective plumes from below rather than by the downward advection of high-entropy air from above.

Further speculation would be out of place in this observational paper. However, the above discussion shows that the Galileo lightning data have broad implications for the dynamics of Jupiter’s atmosphere.

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