Imaging of volcanic activity on Jupiter's moon Io by Galileo during the Galileo Europa Mission and the Galileo Millennium Mission.

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Abstract. The Solid-State Imaging (SSI) instrument provided the first high- and medium-resolution views of Io as the Galileo spacecraft closed in on the volcanic body in late 1999 and early 2000. While each volcanic center has many unique features, the majority can be placed into one of two broad categories. The “Promethean” eruptions, typified by the volcanic center Prometheus, are characterized by long-lived steady eruptions producing a compound flow field emplaced in an insulating manner over a period of years to decades. In contrast, “Pillanian” eruptions are characterized by large pyroclastic deposits and short-lived but high effusion rate eruptions from fissures feeding open-channel or open-sheet flows. Both types of eruptions commonly have ~100-km-tall, bright, SO2-rich plumes forming near the flow fronts and smaller deposits of red material that mark the vent for the silicate lavas.

1. Introduction

Io provides a look at living volcanic processes that died millions or billions of years ago elsewhere in our solar system, acting like a “Jurassic Park” for volcanologists. The end of the Galileo Europa Mission (GEM) and the beginning of the Galileo Millennium Mission (GMM) provided the best spatial resolution images of Io to date. Orbits 124-127 of the Galileo spacecraft took place in a time span of five months, providing the temporal resolution to track the evolution of 100-m-scale volcanic features.

Earlier data from the Voyager and Galileo spacecraft and the Hubble Space Telescope, in conjunction with decades of intensive ground-based telescope observations, provided a wealth of information on this volcanically hyperactive body. Theoretical calculations showed that the tidal stresses that wrack Io as it moves along its resonant orbit between Jupiter and Europa generate enough heat to melt its rocky interior [e.g., Peale et al., 1979; Schubert et al., 1981; Ojakangas and Stevenson, 1986; Fischer and Spohn, 1990]. The two Voyager
spacecraft flew by Io in 1979, providing a stunning view of active plumes of sulfurous volcanic gasses; massive caldera-like pits overflowing with warm lava; long yellow, red, orange, and black lava flows; and a host of enigmatic tectonic features [e.g., Smith et al., 1979a; Strom et al., 1981; Pearl and Sinton, 1982; Schaber, 1982]. From the temperatures and colors of the lavas, the general consensus was that sulfur volcanism dominated the surface of Io with silicate magmas mostly confined to the lower crust [e.g., Smith et al., 1979b]. Meanwhile, Earth-based infrared telescopic observations tracked the thermal emission from active volcanism on Io [e.g., Witteborn et al., 1979; Goguen et al., 1988; Veeder et al., 1994], providing much better temporal and spatial coverage of the volcanism. These studies eventually suggested infrequent but cataclysmic silicate eruptions [e.g., Johnson et al., 1988; Blaney et al., 1995; Spencer et al., 1997; Stansberry et al., 1997; Howell et al., this issue]. The ground-based observations have been complemented by Hubble Space Telescope images that have tracked surface changes and determined the compositions of some of the volcanic plumes [e.g., Sartoretti et al., 1995; Spencer et al., 2000b]. These new data, and the reanalysis of the Voyager data, produced a picture of Io in which sulfurous and silicate volcanism were both active [e.g., Cloos and Carr, 1980; Lunine and Stevenson, 1985; Carr, 1986; McEwen et al., 1989; Spencer and Schneider, 1996].

The arrival of the Galileo spacecraft into the Jovian system in late 1995 opened a new era in monitoring the volcanism on Io. Both the Solid-State Imaging (SSI) camera and the Near-Infrared Mapping Spectrometer (NIMS) have been used to monitor the thermal emission and distribution of volcanic products. SSI has seen many of the same types of volcanic activity that Voyager saw (gaseous plumes and effusive lava flows) as well as explosive silicate eruptions that had not been seen by Voyager [McEwen et al., 1998a; McEwen et al., 2000]. SSI eclipse observations have also revealed a number of locations where very high temperature silicate volcanism is active [McEwen et al., 1997, 1998a, 1998b]. The best constraints on lava temperatures come from the coanalysis of the SSI and NIMS data [Davies et al., 1997; McEwen et al., 1998b; Davies et al., this issue]. The NIMS instrument has also been used to monitor the temporal evolution of nearly 100 volcanic centers [Lopes-Gautier et al., 1997, 1999].

However, this monitoring came from relatively distant, low-resolution observations. The end of GEM and the start of GMM have allowed Galileo to move in close to Io, providing a second revolution in our understanding of its intense volcanism. The primary objectives of the high- and medium-resolution images were threefold: (1) identify the processes that produce the various enigmatic tectonic landforms, (2) identify the processes that produce the various volcanic landforms, and (3) place tighter constraints on the temperature (and indirectly, composition) of the lavas. This paper primarily discusses the latter two objectives. The mountain observations are detailed by Turtle et al. [this issue].

The outline of this paper is to first provide a record of the decisions and accidents that produced the data set we now have. This documents the constraints, assumptions, and biases we labored under while making these observations. In particular, we feel it necessary to explain why we were not able to deliver some of the images that we had planned with the help of many persons outside the Galileo SSI Team. Second, this paper provides the basic descriptions of what we found in the images. We strive to keep these observations unainted by our interpretations, but the assumptions and expectations described earlier are important to keep in mind. Third, we provide our initial interpretations of the active processes at the individual volcanic centers that were well imaged. Some of these interpretations are highly speculative and will probably evolve as more careful coanalysis of the different data sets collected by Galileo, Voyager, and Earth-based telescopic observations are completed. We end with some broad generalizations gleaned from the new data.

However, before proceeding, a note must be made on the terminology used to describe Ionian features. A major problem arises from the way features on Io are named. Volcanic plumes have names (e.g., Pele) but no general term. Thus the name “Pele” used alone should refer only to the Pele plume. However, in this paper we often use the plume name to designate the entire volcanic complex (thus the name “Pele” would refer to the plume, plume deposits, plume vent, lavas, etc.). To distinguish the different parts of the volcanic complex, we use phrases such as “the Pele plume” or “the Pele lava lake.” Low-resolution images have also caused special problems. For example, the new images now reveal that the Maui and Amirani plumes formed over the same flow field.

Another problem unique to Io is the use of the term “patera.” Patera has been often used interchangeably with “caldera,” but a patera is defined as an irregular or complex depression with scalloped edges. Calderas are depressions resulting from the evacuation of a shallow magma chamber. While many paterae do appear to be calderas, others appear to be result of more complex interactions between volcanism and tectonism. For these patera, we also use the term “volcano-tectonic depression” to emphasize their more complex origins.

Other jargon is specific to the Galileo missions. While we attempt to minimize the use of spacecraft-specific terminology, some of these terms are necessary in order to identify individual observations. As the Galileo spacecraft was placed into a highly elliptical orbit around Jupiter, data collection has been concentrated around the periapsis of each orbit. The observations are thus most naturally divided by orbit number. Each orbit has also had a targeted flyby of one of the Galilean satellites, which is identified by a letter in front of the orbit number. For example,

<table>
<thead>
<tr>
<th>Table 1. Galileo Orbits During GEM and GMM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mission</strong></td>
</tr>
<tr>
<td>GEM</td>
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<td>GEM</td>
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<td>GEM</td>
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<td>GMM</td>
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<td>GMM</td>
</tr>
</tbody>
</table>
orbit E24 was the 24th orbit of the Galileo spacecraft around
Jupiter, during which it passed closest to Io.

The Galileo observations are also divided based on the mission
during which the data were collected. The observations during
the Galileo Mission (orbits G1-E11) are described in McEwen et
al. [1998a]. In this paper we describe the observations during
the Galileo Europa Mission (GEM) and the Galileo Millennium
Mission (GMM). GEM was the first extended mission of the
Galileo spacecraft, ending with close flybys of Io. The
spacecraft was found to be largely functional after absorbing
nearly 3 times the radiation that it was designed to survive,
a further extension of the Galileo mission was proposed, leading
to the GMM. The dates of the different orbits and mission phases
are listed in Table 1.

2. Observations

Io lies deep within the radiation belts surrounding Jupiter,
making it particularly hazardous for spacecraft to visit. For this
reason, the close encounters with Io were deferred until the end
of GEM. These Io encounters were fully expected to kill the
spacecraft. While Galileo survived all the Io flybys, the
uncertainty in how it and the SSI camera would function in the
high-radiation environment, and the various anomalies induced by
radiation damage, were major considerations in planning the
Io observations.

The other limitations of the Galileo spacecraft had become
essentially routine after more than 3 years of operating in Jupiter
orbit. The three key resources that were always in short supply
were (1) time at closest approach, (2) space on the tape recorder,
and (3) downlink through the backup low-gain antenna to the
NASA Deep Space Tracking Network. The limited allocations of
these key resources forced many difficult decisions in both the
acquisition of data and the choices of what data to erase without
playing back.

The Galileo Europa Mission had three phases (see Table 1).
Orbits E12-E19 were dedicated to detailed observations of
Jupiter's icy moon Europa. Distant monitoring of Io by SSI was
conducted on orbits E12, E14, and E15. Orbits C20-C23 were
used to lower Galileo's perijove closer to Io, providing an
opportunity to collect context images of Io prior to the close
flybys. A global overview of Io was obtained in orbits C21 and
C22. E24 and I25 were the last two orbits of the GEM, providing
the first high-resolution views of Io. The Galileo Millennium
Mission retroactively included the close flybys of Europa and Io
in orbits E26 and I27 but was focused on joint observations of
the Jovian system by Galileo and Cassini during orbit G29.

2.1. Orbits E12-C20

The long-range monitoring of Io that had been conducted in
1996-1997 during the Galileo prime mission [McEwen et al.,
were selected to help plan for the close flybys and for specialized
scientific goals. However, systematic monitoring of Io was not
an explicit goal of GEM.

Another consideration in planning imaging during GEM was
that the deterioration of the spacecraft with age caused significant
portions of the planned data to be lost. For example, there was a
progressive degradation of the spacecraft gyroscopes, especially
while being bombarded by high-energy radiation. This caused
much larger pointing errors in the Io observations from 1998
onward than those during the Galileo prime mission. These
pointing errors produced gores in some mosaics, large amounts of
smear in long-exposure images, and even led to entirely missing
Io in some cases. Observations in orbits E12 and E15 were lost
due to pointing errors. Other problems, associated with the
spacecraft's electrical systems, caused the loss of all Io
observations planned for orbits E18 and E19 (Table 1). Software
patches that worked around the problem were eventually
successfully implemented. Despite all the technical problems
and a massive reduction in personnel, the Jet Propulsion
Laboratory (JPL) engineers did wonders to keep Galileo working
well past its warranty.

In E14 a single clear filter image of the Pillan region, a 6-
filter, 12-frame mosaic of the anti-Jovian hemisphere and an
eclipse observation were acquired (Table 2). Pillan was the site
of the single largest new eruption on Io observed by Galileo
[McEwen et al., 1998a], and monitoring the evolution of this
eruption was considered a very high priority. The Pillan image

Table 2. Io Observations During Orbits E11-C20

<table>
<thead>
<tr>
<th>Observation</th>
<th>Number of Frames</th>
<th>Resolution (km/pixel)</th>
<th>Filters</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>E11 TOPO</td>
<td>1</td>
<td>9.5</td>
<td>CLR</td>
<td>sub-Jovian hemisphere</td>
</tr>
<tr>
<td>E11 LOWPHA</td>
<td>1</td>
<td>10.3</td>
<td>765, RED, GRN, VLT</td>
<td>low phase angle photometry</td>
</tr>
<tr>
<td>E11 CULANN</td>
<td>3</td>
<td>9.2</td>
<td>RED, GRN, VLT</td>
<td>context and changes in Amirani-Emakong region, Prometheus plume on limb</td>
</tr>
<tr>
<td>E11 VOLUND</td>
<td>3</td>
<td>8.7</td>
<td>RED, GRN, VLT</td>
<td>context and changes around Prometheus, Zamama plume</td>
</tr>
<tr>
<td>E11 MARDUK</td>
<td>3</td>
<td>8.1</td>
<td>RED, GRN, VLT</td>
<td>context and changes around Marduk, Plume on limb</td>
</tr>
<tr>
<td>E11 PILIAN</td>
<td>3</td>
<td>7.9</td>
<td>RED, GRN, VLT</td>
<td>changes around Marduk, Plume on limb</td>
</tr>
<tr>
<td>E11 LOKI</td>
<td>3</td>
<td>10.4</td>
<td>RED, GRN, VLT</td>
<td>changes around Pele, Loki on the limb</td>
</tr>
<tr>
<td>E11 KANEHIL</td>
<td>3</td>
<td>19.2</td>
<td>RED, GRN, VLT</td>
<td>changes around Kanehikili</td>
</tr>
<tr>
<td>E11 ECLIPS2</td>
<td>4</td>
<td>13.6</td>
<td>CLR, 968</td>
<td>centered on Pele</td>
</tr>
<tr>
<td>E14 CONTEX</td>
<td>1</td>
<td>2.6</td>
<td>CLR</td>
<td>context for Pillan in E24</td>
</tr>
<tr>
<td>E14 POLAR</td>
<td>12</td>
<td>2.9</td>
<td>968, 889, 756, RED, GRN, VLT</td>
<td>Prometheus/Zamama region change detection</td>
</tr>
<tr>
<td>E14 ECLIPS2</td>
<td>4</td>
<td>11.3</td>
<td>CLR, 968</td>
<td>centered on Zamama</td>
</tr>
<tr>
<td>E15 HIPHASE</td>
<td>3</td>
<td>14.0</td>
<td>RED, GRN, VLT</td>
<td>high phase angle photometry</td>
</tr>
<tr>
<td>E15 KANEHIL</td>
<td>3</td>
<td>12.4</td>
<td>RED, GRN, VLT</td>
<td>changes around Kanehikili</td>
</tr>
<tr>
<td>E15 ECLIPS1</td>
<td>6</td>
<td>13.8</td>
<td>CLR, 968, RED, GRN, VLT</td>
<td>only CLR and 968 played back</td>
</tr>
<tr>
<td>E15 ECLIPS2</td>
<td>6</td>
<td>13.2</td>
<td>CLR, 968, RED, GRN, VLT</td>
<td>glowing atmosphere of Io</td>
</tr>
<tr>
<td>E15 ECLIPS3</td>
<td>6</td>
<td>10.8</td>
<td>CLR, 968, RED, GRN, VLT</td>
<td>glowing atmosphere of Io</td>
</tr>
<tr>
<td>E15 ECLIPS4</td>
<td>6</td>
<td>11.3</td>
<td>CLR, 968, RED, GRN, VLT</td>
<td>glowing atmosphere of Io</td>
</tr>
</tbody>
</table>

aCLR = clear, VLT = violet, GRN = green, RED = red, 756 = 756-nm, 889 = 889-nm, and 968 = 968-nm.
showed the floor of the patera covered by new dark lavas and provided our best view of the topographic features surrounding the site of the 1997 eruption. It was also taken with a lighting geometry identical to orbit I24, providing the best context available for the high-resolution observation. The color mosaic was the highest-resolution color SSI data to date and showed many interesting features, including new details of the active Zamama plume.

In E15, images planned for continued monitoring of the changes at Pillan were lost but 3-color global monitoring mosaics and color eclipse observations of Io's atmosphere and hot spots were acquired [Geissler et al., 1999b]. Despite multiple attempts, no SSI data of Io were successfully returned from orbits E16-C20.

Various global and regional results from these distant monitoring images are reported by Geissler et al. [1999a, this issue] and Phillips [2000]. The plumes and hot spots seen during the entire Galileo mission are summarized in Tables 3a and 3b.

2.2. Orbits C21-C23

Observations during C21 were primarily intended to provide context for the later higher resolution images. Simultaneously, these images were to help quantify the changes on the surface of Io since the last time it had been extensively imaged in orbit E14, 14 months earlier [Phillips, 2000]. Limits in available downlink and tape led to less than optimal coverage, as evidenced by the gaps in the plume search observations (see Table 4). The C21 sequence executed properly and playback was relatively uneventful. Eighty-four of the 114 frames acquired were at least partially played back. The planning and playback of the observations are detailed below.

The anti-Jovian hemisphere was imaged at 1.3 km/pixel in the green filter and at 2.6 km/pixel in the violet, red, and 756-nm filters (Plate 1). However, the red filter images were not played back. This observation provided 3-color context information for the high-resolution images collected during the later close flybys. As described in the section 3, the combination of kilometer per pixel color information with ~100 m/pixel monochromatic data greatly improved our ability to interpret both data sets. In particular, the association between diffuse red material and volcanic vents became especially clear after combining the C21 color data with both high-resolution SSI images and NIMS thermal data.

The green filter images were also the highest-resolution images of Io acquired by Galileo up to that time. This mosaic allowed discoveries such as the determination that the Amirani and Maui plumes were produced by the same lava flow field.

<table>
<thead>
<tr>
<th>Observation</th>
<th>Number of Frames</th>
<th>Resolution (km/pixel)</th>
<th>Filters</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>COLOR1</td>
<td>32</td>
<td>2.6</td>
<td>756, VLT</td>
<td>anti-Jovian Hemisphere combines with COLOR1</td>
</tr>
<tr>
<td>ALBEDO1</td>
<td>16</td>
<td>1.3</td>
<td>GRN</td>
<td>967 and 889 combine with COLOR1</td>
</tr>
<tr>
<td>ALBEDO3</td>
<td>7</td>
<td>1.3</td>
<td>968, 889, 756, RED, GRN, VLT, CLR</td>
<td>stereo with 124 observation</td>
</tr>
<tr>
<td>STEREO1</td>
<td>12</td>
<td>1.4</td>
<td>CLR</td>
<td>plume search over Pele</td>
</tr>
<tr>
<td>PLUME1</td>
<td>2</td>
<td>3.6</td>
<td>VLT</td>
<td>plume search</td>
</tr>
<tr>
<td>PLUME3</td>
<td>2</td>
<td>5.4</td>
<td>VLT</td>
<td>plume search</td>
</tr>
<tr>
<td>PLUME4</td>
<td>1</td>
<td>6.0</td>
<td>VLT</td>
<td>plume search</td>
</tr>
<tr>
<td>PLUME5</td>
<td>1</td>
<td>6.8</td>
<td>VLT</td>
<td>plume search (only VLT played back)</td>
</tr>
<tr>
<td>PLUME6</td>
<td>3</td>
<td>8.2</td>
<td>RED, GRN, VLT</td>
<td>plume search (only VLT played back)</td>
</tr>
<tr>
<td>PLUME7</td>
<td>1</td>
<td>9.8</td>
<td>VLT</td>
<td>plume search</td>
</tr>
<tr>
<td>PLUME8</td>
<td>3</td>
<td>11.8</td>
<td>RED, GRN, VLT</td>
<td>Pillan surface monitoring</td>
</tr>
<tr>
<td>PLUME9</td>
<td>1</td>
<td>13.8</td>
<td>VLT</td>
<td>plume search</td>
</tr>
<tr>
<td>PLUME10</td>
<td>2</td>
<td>8</td>
<td>GRN, VLT</td>
<td>plume search (only VLT played back)</td>
</tr>
<tr>
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<td>9.6</td>
<td>GRN, VLT</td>
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<tr>
<td>PLUME12</td>
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<td>10.8</td>
<td>GRN, VLT</td>
<td>plume search (only VLT played back)</td>
</tr>
<tr>
<td>PLUME13</td>
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<td>12.5</td>
<td>GRN VLT</td>
<td>plume search (only VLT played back)</td>
</tr>
<tr>
<td>PLUME14</td>
<td>2</td>
<td>14.1</td>
<td>968, CLR</td>
<td>eclipse over Loki</td>
</tr>
<tr>
<td>NACL01</td>
<td>2</td>
<td>10</td>
<td>GRN, CLR</td>
<td>sodium cloud in sunlight, lo in eclipse</td>
</tr>
<tr>
<td>NACL02</td>
<td>1</td>
<td>1.3</td>
<td>CLR</td>
<td>sodium cloud</td>
</tr>
<tr>
<td>PLUME15</td>
<td>2</td>
<td>15.1</td>
<td>GRN, VLT</td>
<td>surface change monitoring</td>
</tr>
<tr>
<td>PLUME16</td>
<td>2</td>
<td>16.5</td>
<td>GRN, VLT</td>
<td>surface change monitoring</td>
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Table 5. Observations During C22

<table>
<thead>
<tr>
<th>Observation</th>
<th>Number of Frames</th>
<th>Resolution (km/pixel)</th>
<th>Filters</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLUSUR1</td>
<td>2</td>
<td>17</td>
<td>GRN, VLT</td>
<td>plume search</td>
</tr>
<tr>
<td>IOGEO1D</td>
<td>1</td>
<td>10</td>
<td>GRN</td>
<td>geodesy (shape of Io)</td>
</tr>
<tr>
<td>PLUSUR2</td>
<td>1</td>
<td>11</td>
<td>VLT</td>
<td>plume search</td>
</tr>
<tr>
<td>PLUSUR3</td>
<td>1</td>
<td>13</td>
<td>VLT</td>
<td>plume search</td>
</tr>
<tr>
<td>PLUSUR4</td>
<td>2</td>
<td>14</td>
<td>GRN, VLT</td>
<td>plume search (playback VLT only)</td>
</tr>
<tr>
<td>PLUSUR7</td>
<td>2</td>
<td>15</td>
<td>GRN, VLT</td>
<td>plume search</td>
</tr>
<tr>
<td>PLUSUR8</td>
<td>2</td>
<td>16</td>
<td>GRN, VLT</td>
<td>plume search</td>
</tr>
<tr>
<td>PLUSUR9</td>
<td>2</td>
<td>16</td>
<td>GRN, VLT</td>
<td>plume search (playback VLT only)</td>
</tr>
<tr>
<td>PLUSUR10</td>
<td>2</td>
<td>16</td>
<td>GRN, VLT</td>
<td>plume search (playback VLT only)</td>
</tr>
<tr>
<td>PLUSUR11</td>
<td>2</td>
<td>16</td>
<td>GRN, VLT</td>
<td>plume search</td>
</tr>
<tr>
<td>PLUSUR12</td>
<td>2</td>
<td>16</td>
<td>GRN, VLT</td>
<td>plume search</td>
</tr>
</tbody>
</table>

The Amirani flow field contains the longest known active lava flows in the solar system.

A 7-color observation covering some of the most active volcanic centers was also acquired. Because of the limited downlink, only a portion of the 889- and 989-nm filter images were played back. These were combined with the 4-color global images to provide 6-color coverage over a small region near Zamama. However, the wobble in the pointing of the spacecraft reduced the full color coverage to the equivalent of only 1/8 of a frame.

The anti-Jovian hemisphere was also imaged at 1.4 km/pixel in the clear filter to provide stereo coverage with an I24 observation. However, large sections of this observation were never played back because (1) they did not overlap the area to be imaged in I24, (2) they were near the limb of Io and provided only very oblique views, and (3) of the limited available downlink.

A sequence of 18 observations searching for active volcanic plumes was also conducted. Two of these observations were adjusted to image the sodium cloud coorbiting with Io (as well as Io in eclipse), eight others were taken in multiple filters to provide information on the surface of Io, and one was taken while Io was in Jupiter’s shadow, allowing hot spots to be imaged. Due to limited downlink, the color information was not returned from most of these plume search images. Furthermore, the sodium cloud images were clipped too close to Io’s limb.

In orbit C22, imaging of Io was restricted to a 12-frame sequence of images completing the search for active plumes started in C21 and a single frame for cartography and geodesy (Table 5). The spacecraft executed its instructions as expected and only 3 of the 19 images were completely deselected for playback.

The set of 25 low-resolution violet filter images acquired in orbits C21 and C22 provides a partial inventory of active plumes. Longitudes 0°-156° and 256°-360° were covered with the bright limb spaced about every 10 degrees. Image resolution ranged from 5 to 17 km/pixel, but useful resolutions were considerably worse due to lossy compression and smear. The only plumes seen on the bright limbs were Masubi and Amirani. While surface changes suggested that the Masubi plume had been active during GEM, this was the first time a plume was seen over Masubi (Figure 1) since the Voyager flybys in 1979 [Phillips, 2000]. An eclipse image in C21 (Figure 2) revealed the persistence of the Marduk and Kanahelkili plumes. Pele was not detected but was probably active. Pele is usually invisible to SSI but is more prominent at ultraviolet wavelengths [Spencer et al., 1997, 2000b]. Longitudes 156°-256° were not imaged in a geometry where a plume would be expected to be visible on the bright limb, but the Prometheus plume rose high enough to be seen as a bright mushroom beyond the terminator. Other Galilean-era plumes Acala and Culann were not seen, but have only been detected previously in eclipse, and the C21 eclipse geometry did not place these plumes on the limb. Zamama was not detected even though it was near the terminator, so it was significantly less active or bright than it was in orbit E11. Ra has not been seen since orbit G1, and Pillan has not been detected since orbit E11, so these plumes were also probably inactive in the summer of 1999. We conclude that the level of plume activity during C21-

Figure 1. Grayscale reproduction of color mosaic using data from C21 observations COLOR01 and ALBEDO01 showing the Masubi plume. Image resolution is 1.3 km/pixel in the green filter and 2.6 km/pixel in the green and violet. The plume is made more visible in this figure than in Plate 1 by greatly enhancing the brightness and contrast in only the part of the image that is beyond the limb of Io.
The logic for the partial frames was that if the radiation noise was so great that even the summation mode images were useless, then the uppermost few lines of the full resolution images still might be interpretable because they are the first lines read off of the detector. These contingency frames were placed at the end of the longer high-resolution observations so they were generally off of the target of interest.

Unfortunately, the summation mode did not function properly. In hindsight, the seemingly inconsequential problems encountered in the orbit C23 images were a warning that the camera was damaged. The problem was traced to the timing of the readout of the 2x2 blocks. In many images, instead of having four adjacent pixels summed, 2 pixels from the right side of the image were added to 2 pixels on the left side of the image. There was also a 7-pixel offset between the even and odd lines. Because this problem was well-characterized, it was possible to generally reconstruct these images. The scrambled raw data was unscrambled by a program developed at JPL using the LabVIEW software from National Instruments of Austin, Texas. However, the reconstructed images are not a proper mathematical solution for the original image since one is solving for 800x800 unknowns given only 400x400 knowns. Instead, an iterative algorithm is used that produces the sharpest image. As such, the photometric calibration of the images is lost, and some artifacts are introduced. Extreme caution needs to be used in interpreting these reconstructed images.

A smaller number of images were scrambled in a more complicated manner. Some portions of these images had vertical seven-pixel bands that had no summation done to them, providing bits of full-resolution, unadulterated data. Other portions of the same images had addition of pixels from the far left and far right of the frame, and other portions had black vertical stripes with no returned data. While small parts of these frames contain useful data, to date, no algorithm has been built to reconstruct the images.

Finally, these anomalies also wrote image data into portions of the frame where the zero DN level is recorded within the camera. Because of this, the brightness level within each image fluctuates from the top to the bottom of the frame. In several cases the values within the image rose beyond the saturation of the detector, leaving areas with only a bright smear.

Another unrelated problem with the spacecraft put it into “safer mode” just 7 hours before closest approach. JPL engineers quickly determined that the problem was a stuck bit in the flight computer and were able to locate the approximate location of the bad bit. The encounter sequence was restarted just before closest approach, but large amounts of magnetosphere data were never collected, freeing enough downlink to have almost all the images played back with lossless compression. The reconstruction of the garbled images was greatly simplified by the fact that most of the data were returned without compression artifacts. The observations during orbit I24 are summarized in Table 6, and those targeting volcanic features are described in detail below. Unless otherwise noted, each of these observations was returned in its entirety with lossless compression, but smaller gaps in the images resulting from data drop outs during playback were often not filled.

### 2.3. Orbit I24

Going into our first opportunity for high-resolution imaging of Io, we faced a huge uncertainty in how the spacecraft and camera would function in the high-radiation environment. In order to minimize the effect of radiation-induced noise in the images, the SSI camera had a special mode in which 2x2 blocks of pixels were summed and read off the CCD quickly [Klaasen et al., 1997]. This had the effect of halving the spatial resolution of the images but decreasing by a factor of 3.7 the time that radiation noise could build up. This camera mode also had the benefit of providing an immediate 4:1 compression of the data, using much less tape than other camera modes. During the close approach to Io, 122 images were collected in this “2x2 summation” mode, with only 10 partial frames recorded in the full-resolution mode.
Plate 1. False-color mosaic using data from C21 observations COLOR01 and ALBEDO01. North is to the top in all figures, unless otherwise noted. Violet, green, and 756-nm filters were used, extending the red colors into the shortest infrared. The resolution of the mosaic is 1.3 km/pixel but only the green data were acquired at that resolution. In general, bright areas correspond with SO$_2$-rich deposits (but see Geissler et al., this issue), red deposits are likely to include short-chained sulfur, and dark areas are recent (predominantly silicate) lava flows [e.g., Geissler et al., 1999]. These data provide the best context for the later high-resolution and medium-resolution data sets. It also has allowed the merging of color information with medium-resolution observations in the later orbits. Volcanic regions examined in detail in orbits 124-127 are labeled.
Table 6. Observations During I24

<table>
<thead>
<tr>
<th>Observation</th>
<th>Number of Frames</th>
<th>Resolution (km/pixel)</th>
<th>Filters</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>PELE1</td>
<td>13 (12)</td>
<td>0.014-0.030</td>
<td>GRN, CLR</td>
<td>Pele lava lake in the dark (alternating long and short exposures)</td>
</tr>
<tr>
<td>PILLAN1</td>
<td>13 (12)</td>
<td>0.009-0.019</td>
<td>CLR</td>
<td>1997 Pillan lava flows</td>
</tr>
<tr>
<td>COLCHS1</td>
<td>11 (10)</td>
<td>0.009-0.016</td>
<td>CLR</td>
<td>Ot Mons</td>
</tr>
<tr>
<td>ZAMAMA1</td>
<td>13 (12)</td>
<td>0.021-0.041</td>
<td>CLR</td>
<td>Zamama flow field and plume vent area</td>
</tr>
<tr>
<td>PROMTH01</td>
<td>16 (14)</td>
<td>0.036-0.015</td>
<td>GRN, CLR</td>
<td>2 strips targeted on main flow field context of Ot Mons</td>
</tr>
<tr>
<td>COLCHS2</td>
<td>2 (2)</td>
<td>0.160</td>
<td>CLR</td>
<td>stereo with I27 observation color mosaic of Prometheus. Visible filters highly scrambled.</td>
</tr>
<tr>
<td>TOHL1</td>
<td>6 (6)</td>
<td>0.188</td>
<td>CLR</td>
<td>regional mosaic over Isus, Donar, Volund and Zamama.</td>
</tr>
<tr>
<td>FROMTH2</td>
<td>9 (6)</td>
<td>0.12-0.23</td>
<td>967, 889, 756, RED, GRN, VLT</td>
<td>Dorion Mons and surroundings</td>
</tr>
<tr>
<td>ZAMAMA2</td>
<td>18 (18)</td>
<td>0.37-0.41</td>
<td>CLR</td>
<td>regional mosaic over Amirani, Skythia, Gish-Bar, and surroundings</td>
</tr>
<tr>
<td>DORIAN2</td>
<td>4 (4)</td>
<td>0.45</td>
<td>CLR</td>
<td>near-terminator view of Hiita and surroundings</td>
</tr>
<tr>
<td>AMSKG1</td>
<td>18 (18)</td>
<td>0.47-0.51</td>
<td>CLR</td>
<td>Pillan plume search</td>
</tr>
<tr>
<td>TERMAP1</td>
<td>7</td>
<td>0.285-0.57</td>
<td>CLR</td>
<td>hemispheric stereo with I24</td>
</tr>
<tr>
<td>PILLAN2</td>
<td>2</td>
<td>1.3</td>
<td>RED, VLT</td>
<td>Pele hemispheric color observation</td>
</tr>
<tr>
<td>STEREO1</td>
<td>12</td>
<td>1.5</td>
<td>CLR</td>
<td>eclipse</td>
</tr>
<tr>
<td>GLOCAL1</td>
<td>6</td>
<td>6.5</td>
<td>967, 889, 756, RED, GRN, VLT</td>
<td></td>
</tr>
<tr>
<td>ECLIPS1</td>
<td>6</td>
<td>15</td>
<td>967, RED, GRN, VLT, CLR</td>
<td></td>
</tr>
</tbody>
</table>

*Number in parentheses is the number of frames that were scrambled by the camera anomaly.

shortest infrared radiation, so it is unable to detect lava more than a few minutes old [Keszthelyi and McEwen, 1997; McEwen et al., 1997]. Because Pele saturated the SSI detector in most low-resolution eclipse observations, we were concerned that, at high resolution, the small hot areas would completely overload the detector. Thus we alternated the exposure times between 4.2 and 48 ms. Also, the final frame was taken through the green filter. If a pixel within the nighttime green-filter image were saturated, it would have indicated a brightness temperature in excess of 1800 K. The observation had >50% overlap between adjacent frames to allow a coherent mosaic to be constructed from either the long- or short-exposure frames alone. Also, the images were acquired while the spacecraft was in an orientation where about 1/3 of the frames were expected to be partially obscured by the spinning booms of the spacecraft.

These images were first returned at high (lossy) compression to determine which frames contained useful information. In the end, the longer-exposure clear frames were all played back with lossless compression, but the short-exposure and green-filter frames were not.

Figure 3 shows the mosaic of the reconstructed long-exposure frames from Pele in darkness. We think the location of the sinuous glowing line corresponds to the margin of the Pele Patera, as shown at the bottom, because it has the right size and scalloped shape typical of patera margins. The glowing area is ~10 km long and no more than 100 m wide, suggesting a total hot area detected <1 km². The isolated glowing spots seen to the west of the main glowing line fall within the fracture that was filled with dark lava in the Voyager image. This hot area has been interpreted to be the active margin of a lava lake [McEwen et al., 2000].

Much to our surprise, no pixel is saturated in even the long-exposure images. The brightest pixel can be explained by thermal emission from a surface at ~1000 K. SSI is unable to detect surfaces below 700 K [McEwen et al., 1997]. These low temperatures are a puzzle because earlier NIMS observations suggested an area of ~0.5 km² at temperatures of 1300-1400 K spread over the Pele region [Davies et al., this issue]. More distant SSI observations in I24 and earlier orbits required an area of >10 km² at 1000 K to explain the detected thermal emission [McEwen et al., 1998a, 1998b].

2.3.2. PILLAN1. Pillan was the site of the single largest new eruption seen by the Galileo spacecraft and provided the clearest evidence to date of extremely hot lavas on Io [McEwen et al., 1998b]. It is described and modeled by Williams et al. [this issue(b)]. I24 provided an opportunity to examine a sliver of the 5600 km² of new lava flows produced by this eruption at high resolution (9-19 m/pixel). The region was very near the evening terminator, producing excellent lighting conditions for seeing topographic features. However, the area was also dark enough to make the selection of exposure times difficult: longer exposure would lead to a better signal-to-noise ratio but increased smearing of the image. In the end, it was decided to use a 21-ms exposure time for the first six frames and 12-ms for the remainder. The other major problem with this observation was the complete lack of intermediate resolution context. Because this part of Io rotated out of view from the spacecraft, it was not possible to take lower resolution context frames later in the encounter. Nor was this area visible in daylight during close encounters with Io in later orbits. We did not expect to be able to place the ~10 m/pixel images into the preexisting 2.6 km/pixel context.

Figure 4 shows the mosaic of reconstructed frames over Pillan. The last, never-garbled, partial frame is also shown in Figure 4 but does not appear to overlap the other images. The reconstructed images have an effective resolution of about 20-30 m/pixel but the partial frame has a resolution of 9 m/pixel. The degradation in the summation-mode images is readily apparent in Figure 4. For example, the mosaic was intended to traverse from dark flows to bright plains. But with the floating zero level, it is difficult to confidently determine albedo levels. However, Photo-Polarimeter Radiometer (PPR) thermal data were acquired simultaneously with the SSI images, indicating that the transition from warm lava to cold plains takes place around the middle of the mosaic [Spencer et al., 2000a]. The entire region shows a very complex, rough surface with pits and domes. Shadow measurements within the ungarbled frame indicate that the height of the domes and the depth of the pits are generally of the order of 10 m. Shadow measurements along the western section of the flow field indicate flow thicknesses of 8-10 m.

Larger-scale morphologic features are also evident [Williams et al., this issue(b)]. A channel and a scarp, each about 100 m
of the bright plume. The strip was not able to cover both the eastern and western ends of the dark lava, so preference was given to the larger, eastern end.

When the data were returned, we found that the pointing for the entire observation was shifted about half a frame to the south of where it was planned, missing much of the targeted lava. Figure 5 shows the mosaic of reconstructed images. The dark lavas show a complex crenulated margin with many thin anastomosing fingers. The lack of any visible features within the flow field suggests that the lava surface is relatively bland, but the scrambling and unscrambling of these images may have erased subtle features. We were greatly disappointed that we apparently missed the source of the large plume seen in orbit E14 and earlier. The ride-along I24 PPR data show that the dark lavas were still significantly warmer than the surrounding plains with a distinct peak in thermal output at the point the mosaic passes closest to the plume vent(s) [Spencer et al., 2000a]. Interestingly, this area appears the fuzziest in the SSI mosaic, as if covered by a diffuse plume deposit, but this might only be an artifact of the garbling of these images.

The bright “plains” to the west of the Zamama flow field proved to be covered by a series of bright flows. These flows are narrow (≤1 km wide), relatively long (>10 km), and anastomosing. The flows are also subparallel and appear to be incised into the surrounding materials.

2.3.4. PROMTH01. Prometheus has been dubbed the “Old Faithful” of Io with a prominent plume visible in every image of it taken by the Voyager and Galileo spacecraft. However, a new ~80-km-long lava flow field appeared between 1979 and 1996 and the source of the plume shifted a similar distance. The I24 observation sequence was intended to help determine why the plume had moved, to identify the morphology of the new lava, and to constrain lava temperatures. Two strips of images were placed over the new lavas, one using the clear filter, the other using the green filter. The reasoning was that comparing the clear and green filters would allow us to distinguish between areas with high albedo versus areas with thermal emission (both would look bright in the clear filter images). The major problem that arose was that the green filter images needed relatively long exposures to have adequate signal but long exposure times would result in significant smearing. We chose to underexpose the images and the scrambling effectively halved that signal.

The quality of the clear filter images was adequate though several critical areas were affected by the floating zero level pushing DN to saturation. There is no way to recover these data. The clear filter strip also suffered from a gap in the mosaic where frames failed to overlap. The pointing for both strips was mostly on target.

While the green filter mosaic has a poor signal-to-noise ratio and is of limited use, the clear filter mosaic shows the morphology of the lava flow field (Figure 6). Much like Zamama, the margins of the flow field are intricately crenulated. However, there are no narrow fingers of lava extending from this part of the flow field. Instead, there is a striking mottled albedo pattern within the western end of the flow field. Parts of the flow field appear to be buried by a diffuse mantling deposit, but this could be an artifact of the image unscrambling process. On the eastern margin, the lava has moved between ridges in the surrounding landscape, producing a crenellation that is more a reflection of local topography rather than the natural behavior of the lava. No bright spots attributable to incandescent lava were found in this observation.
Figure 4. Mosaic of the ~10 m/pixel unscrambled images from I24 PILLAN01 showing the morphology of the surface of the 1997 Pillan lava flow field. The ungarbled partial frame does not overlap the mosaic but must lie immediately to the west of the mosaic. The context image is from orbit the E14 near-terminator view and is the highest resolution context available. Because of the greater ~2 orders of magnitude jump in resolution and pointing uncertainties, the location of the strip of I24 images is known only approximately. The surface of the lava flow contains several mysterious pits, which may be spatter ramparts from the primary fissure or from the interaction between hot lava and sulfurous snows. Albedo patterns near these pits are suggestive of rafted lava plates, like those seen on platy-ridged flows on Mars [Keszthelyi et al., 2000]. However, the signal-to-noise ratio is poor. Artifacts of the image reconstruction process, including the missing data in the middle of each frame and the wispy horizontal albedo streaks, are clearly visible in the mosaic. Various ridges and channels are visible farther to the east. The channels and other volcanic features are discussed in more detail by Williams et al. [this issue(b)].
Figure 5. Mosaic of I24 ZAMAMA01 with context and expanded views. The orbit E14 context showed the location of the plume vent that was the target for this observation. However, pointing errors shifted the entire observation to the south, providing views of the convoluted lava flow margins. The images to the west of the dark Zamama flow field show what appear to be bright channels incised into the surrounding plains [Williams et al., this issue(a)]. The ZAMAMA02 observation (Figure 8) provided more information about this volcanic center.
2.3.5. PROMTH02. The second observation of Prometheus was to provide color context for the two narrow strips. Three-color data covered the entire Prometheus region, and three partial frames using the near-infrared filters were placed over the eastern end of the lava to gather color data to constrain the lava compositions.

Some of these images suffered the worst garbling seen in I24. When the reconstructed images are stacked to produce a color view, the effects of the floating zero level and the reconstruction algorithm destroyed all useful color information. However, parts of individual frames provided useful information.

The medium-resolution overview of the Prometheus region proved extremely useful. The three partial frames taken without summation in the infrared filters were not garbled and provided our first medium-resolution view of the eastern end of the Prometheus flow field. Figure 7 shows the ungarbled partial frame within a lower resolution I24 observation. Instead of being a lava flow, this region is actually a lava-filled depression. The patera is 28x14 km, and lava flows spill over the southwest rim. These spillovers produce relatively thin and short flows that have an intensely twisted shape as they weave between the hummocks on the surrounding plateau.

The main Prometheus flow field extends from the southeast corner of the patera. The eastern margin of the flow here is very linear, apparently confined by a tectonically generated topographic scarp. The southern extension of this scarp is visible in the PROMTH01 high-resolution mosaic, but the broader view provided by PROMTH02 was needed to see the tectonic nature of the scarp.

2.3.6. ZAMAMA02. This observation was to provide a regional view of Zamama and the regions to the north and west. Three strips of 6 frames were placed to cover a large variety of Ionian landforms. This included parts of the volcanic features Volund, Isum, Donar, and Zamama. Volund was the site of a plume in 1979. Isum Patera may include a very large lava flow field with at least two distinct hot spots, and Donar Fluctus is a complex flow field.

All the images in this observation were garbled, with the northern strip currently still unreconstructed. Pointing was generally shifted about 1/2 frame to the south, and there are a number of gores in the mosaic.

While the mosaic had a nominal resolution of ~400 m/pixel, the reconstruction process visibly degraded resolution. Furthermore, the Isum region was on the limb, producing a highly foreshortened view. The most useful information came from Zamama itself (Figure 8). Lava flows radiate from a point at the western end of the flow field. The large dark flow field extends WSW from the end of a linear feature (presumably a volcanic fissure) extending east from the central vent. The distribution of lava flows around Zamama requires that the central vent be located at a topographic high. However, this volcanic construct has slopes too shallow to produce shadows or other indications of its height in available images.

The reconstructed images also provide a reasonable view over the southeastern part of Isum. These images show a circular central depression with an apron of radial dark lava flows. The individual lava flows have a narrow, finger-like shape and extend 50 to >150 km from the center of Isum. This produces a frayed outline to the dark apron of Isum. Beyond the dark lavas is a ~20-km-wide diffuse bright deposit, marking the transition to the bright plains of Colchis Regio. The color context from C21 and other earlier low-resolution observations indicate that the western and northern parts of Isum are significantly more complicated.

This observation also provided a good view of Donar Fluctus, a series of lava flows emanating from a ~30-km-diameter patera. While the flows are radial to the patera, only narrow flows are visible extending to the north, east, and south. The two large flow fields extend to the northwest and southwest, toward an enigmatic, teardrop-shaped mountain or mesa (see Turtle et al. [this issue] for more details). These flows appear dark in the
reconstructed I24 images, but the C21 color context shows them to be a dark green rather than the black of typical recent lava flows.

Volund, the source of a major plume during the Voyager flybys in 1979, was also intended to be part of the mosaic. However, because the entire observation shifted to the south, and the northernmost frames have not been reconstructed, we have no new information on Volund.

Figure 7. Mosaic with the never-garbled I24 PROMTH02 756-nm filter partial frame within context from observation I24 STEREO01 taken in the clear filter. The artifacts within the reconstructed violet, green, and red filter images are too great to allow useful color information to be extracted. However, the ~120 m/pixel infrared partial frames provide new insights into Prometheus. The northeastern end of the flow field is a patera with overflows to the southwest. Coanalysis with the NIMS data [e.g., Lopes et al., this issue] and changes detected in earlier low-resolution color data [Phillips, 2000] suggest that the vent is ~15 km south of the patera.

2.3.7. AMSKIGI01. This observation placed three strips of 6 frames over a wide variety of Ionian landforms including Amirani-Mau, Skythia Mons, and Gish-Bar Patera. For the colorized mosaic, see Turtle et al. [this issue].

All the images in this observation were garbled. It was not possible to reconstruct some parts of the Amirani flow field because bright areas were summed with dark areas, leaving almost no information usable for the reconstruction algorithm. Pointing errors also produced a major gore in the mosaic, cutting through the part of the flow field connecting the source of the Voyager era plume named Maui to Amirani. Despite the problems with the mosaic, new details are visible from Amirani-Mau and a number of paterae. The far western end of the flow field (Maui) appears to have been deflected by the foothills of Skythia Mons. Maui Patera, just to the southwest of the terminus of the lava flows, appears to be unrelated to the lavas. The flow field connecting Amirani with Maui is relatively narrow and bifurcates at one point, leaving an island of plains material. The main Amirani flow field extends northward. A number of small isolated dark patches near the northern end of the flow appear to be breakouts of fresh lava from within the main flow. A larger set of breakouts is visible close to the southern end of the Amirani flow field. Plume deposits obscure the join between the "Maui" and "Amirani" flow fields. The source for the lavas is not clear from these images.

The AMSKIGI observation also imaged Gish Bar, Monan, and a number of other unnamed paterae. These are described in more detail by Radebaugh et al. [this issue]. The mountains are described by Turtle et al. [this issue].

2.3.8. PILLAN02. This observation was intended to provide a high-resolution view of the Pillan plume rising over the limb of Io. However, C21/C22 observations showed that the plume had
turned off. There was no time to replan this observation, so it remained in the sequence. This was the only I24 observation to be only partially played back. The partial frames that were played back confirmed that the Pillan plume was not detected.

2.3.9. STERE001. This observation, combined with the C21 STEREO observation, provided topographic information over a large portion of the anti-Jovian hemisphere. These data are still being processed.

2.3.10. GLocol01. This was a low-resolution full-disk color observation intended to monitor the large-scale changes on Io. It was primarily intended as a backup observation in case all the high-resolution images were made useless by radiation noise. These images were taken in one of the full-resolution camera modes that produced ungarbled images. Because of the ample downlink on this orbit, all of this observation was returned.

The major changes in the distribution of different color units around Pillan and Pele seen in this observation are described by Phillips [2000]. Pele Patera was found to be bright in the infrared filters, indicating an amount of thermal emission similar to eclipse observations in earlier orbits. This strongly suggests that Pele was not unusually quiescent at the time of the high resolution PELE01 observation.

2.3.11. ECLIPS01. This was a distant observation intended to monitor the level of activity at the volcanic centers Loki, Pele, and Pillan. Due to the degraded attitude control of the spacecraft, and the long exposures needed for eclipse observations, the images were highly smeared.

The highly smeared eclipse observations are difficult to interpret. The thermal emission from Pele is the dominant signal with a weak signal apparently from Loki. No other hot spots are currently detectable. This confirms that Pillan was much colder in late 1999 than in late 1997 and early 1998 [Davies et al., this issue].

2.4. Orbit I25

I25 was a south polar pass intended to examine the magnetic field of Io. A wide variety of observations were planned, originally depending heavily on the use of summation mode images. After I24, an intense effort was made to modify the sequence to use only full-resolution images. The replanning was complicated by the fact that two full-resolution modes were available for Io data acquisition. One mode simply wrote the image onto tape, allowing the compression ratio (typically 5:1) to be selected during playback. While this allowed the most efficient use of downlink, it used large amounts of tape. The other mode used a compression algorithm that was hard-wired into the camera. This provided 2.4:1 compression of the images before writing to tape. However, once written to tape, these images could not be further compressed during playback. After the damage the camera electronics suffered in C23, it was considered risky to use the camera's built-in compression capability. However, tape was so limited that ~75% of the planned observations would have to be eliminated if no compression was used before writing to tape. In the end, the observations were divided about equally between the two modes. With this compromise, none of the original observations were deleted but most had about half their frames eliminated.

Much of this work was lost to a spacecraft safing event 4 hours before closest approach. Only by heroic efforts over Thanksgiving were JPL engineers able to restart the data collection about 30 minutes after closest approach. The cause of this incident was apparently an incomplete correction for the stuck bit encountered during I24. Seven SSL observations were lost, including all the very high-resolution imaging.

Once again, there was a silver lining to this apparent disaster. There was never enough downlink to return more than a small fraction of the observations planned for I25. But with the high-resolution imaging lost, there was almost exactly enough downlink to return the medium-resolution data that we had successfully acquired. Had the high-resolution data been on tape, it is possible that we would not have played back what turned out to be the most fortuitous of Galileo Io observations. The observations during orbit I25 are summarized in Table 7 and described in detail below.

2.4.1. EMAKNG02. This observation was intended to be the second part of a stereo observation of the Emakong Patera and what was interpreted to be an enigmatic scarp along its margin. Emakong was not known to include an active hot spot, but it is surrounded by large, bright white and yellow, flow-like deposits. Such flows are speculatively interpreted to be sulfur flows. While most of Galileo's efforts were aimed at understanding the high-temperature silicate lavas, it was decided that at least one observation should be dedicated to potential sulfur volcanism. This being the lower resolution observation, it was also intended to provide some additional context for the narrow strip where stereo would be available. While the observation was sharply trimmed due to the limited tape available, it did provide a nearly 100 km x 250 km swath across Emakong Patera and the flows extending out from it to the east and west. This observation was played back in its entirety with ~4:1:1 lossy compression. It is shown by Williams et al. [this issue(a)].

While the stereo information from this observation was lost, the medium-resolution images provided a few new clues to the formation of large, bright lava flows. What was originally interpreted as a scarp with a shadow in low-resolution images turned out to be the margin of the bright lava flow. It is still possible that this western flow margin is controlled by topography, but the scarp does not have the sharp linear nature expected of a tectonic feature. The flow margins on the east are extremely convoluted and appear to have embayed a hummocky area. The center of the flow has a dark channel that appears to start just outside the walls of Emakong Patera. The floor of Emakong Patera contains a low-contrast mottling. The volcanological implications of these observations are discussed in more detail in Williams et al. [this issue(a)].

2.4.2. GIANT01. This observation was intended to examine a chain of large caldera-like depressions at high northern latitudes. This feature was later named Tvashtar Catena. While

<table>
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<th>Table 7. Observations During I25</th>
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<tr>
<td>Observation</td>
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<tr>
<td>EMAKNG02</td>
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<tr>
<td>GIANT01</td>
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<tr>
<td>CULANN1</td>
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<tr>
<td>TERM1</td>
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thought to be inactive. Tvasthar Catena was the largest volcanic depression on Io [Radebaugh et al., this issue], and there were suggestions that volcanic processes at high latitudes were different than those in the equatorial region [Lopes-Gautier et al., 1999; McEwen et al., 2000]. The position of the two frames was carefully adjusted to also cover a mountain south of the depressions. These frames were returned with 3.4:1 - 4:1 lossy compression.

To our happy surprise, we found active lava erupting along the margin of one of the smaller depressed depressions within Tvasthar Catena [McEwen et al., 2000] (Plate 2). The lava was hot enough to overload the detector, producing bleeding within the image. The way the pixels within the SSI detector are connected allows bleeding only in columns. Approximately nine pixels of bleeding will occur downward for each pixel of bleeding up the column. Plate 2 shows the estimated position of the hot feature causing the bleeding if it were only one pixel wide. The estimates of lava temperature critically depend on the number of pixels assumed to contain hot lava. Reasonable assumptions (1-5 pixels) result in brightness temperatures of 1000-1500 K. The ~25-km-long hot area follows the margin of one of the smaller depressions nested within Tvasthar Catena. A dark diffuse deposit extends about 30 km away from the hot area. This has been modeled as a mafic pyroclastic deposit by Wilson and Head [this issue]. Additional features of the paterae and surrounding mountains are described by Radebaugh et al. [this issue] and Turtle et al. [this issue].

2.4.3. CULANN01. This was the highest resolution color observation planned for Io. The Culann region is one of the most colorful parts of Io with bright red, orange, and green areas (Plate 3). It has been the source of a persistent hot spot during the Galileo monitoring. The green material was especially puzzling [Geissler et al., 1999a]. It appeared to be correlated with some paterae, but low-resolution images provided few clues about the processes that produced this material. Because this observation was recorded with the SSI camera's built-in compression algorithm, it could only be played back with 2:4:1 compression. Even with the loss of the high-resolution images, there was not sufficient downlink to return all of this observation. We elected to return all of the green filter frames and trim parts of the violet and red filters.

The high-resolution color view of Culann provided a wealth of insight into the working of Ionic volcanism as well as opening many new questions. The volcanic activity at Culann appears to be centered around a 23 km x 7 km elongated depression. The floor of the depression and the nearby flows are green. This green area is surrounded by a 150- to 170-km-diameter ring of diffuse red material. Lava flows spread radially from the central patera, but the longest, blackest, lava flows extend to the west and northwest. There is a dark sinuous feature that runs down the center of the proximal part of this dark lava. The sinuous feature is marked by localized red deposits and more diffuse yellow and green materials. In the medial portion of the flow, the sinuous line gives way to a series of small (kilometer-scale) lobate dark patches.

Large flows also extend to the southwest of the central patera. However, these flows are mostly colored by the diffuse deposits. The exception is that the distal ends of the flows have a distinct brown color. These flows also appear to be deflected by topography suggestive of a filled depression ~85 km x ~40 km in size. Hummocky plateau/plains material is evident around this possible larger patera.

Tohil Mons and Tohil Patera are also partially visible in this image. Tohil Patera shows an intimate mixing of white, black, green, red, and brownish materials. The bright white material produces a particularly perplexing pattern, suggestive of a very low viscosity fluid filling low areas within the hummocky patera floor. The black, red, green, and brownish materials have lobate margins characteristic of silicate and/or sulfur lava flows.

2.4.4. TERMAP01. While this observation includes a number of volcanic features (especially paterae), it was planned to study mountains on Io and is described by Turtle et al. [this issue]. The paterae and their association with the nearby mountains are described by Radebaugh et al. [this issue] and Jaeger et al. [2001]. Due to the limited tape and downlink resources available during I25, no distant observations (such as the global color and eclipse observations of I24) were planned.

2.5. Orbit E26

2.5.1. General. The primary goal of E26 was to obtain magnetometer data from Europa. Remote sensing was minimal, and only one Io observation was made. While the bulk of SSI's downlink was given to Europa, the small amount of I25 Io data that was on tape was not overwritten in E26 and its playback continued through E26. During the E26 close approach to Europa, the spacecraft did not encounter any problems that the JPL engineers did not anticipate and the sequence executed nominally.

2.5.2. LOKI01. The one new Io observation during E26 was a 5-color view of the hemisphere with Loki and Pele (Table 8). The primary goal was to search for the 0.9 μm absorption feature that had been seen on dark lavas elsewhere on Io and interpreted as magnesium-rich orthopyroxene [Geissler et al., 1999a]. A secondary goal was to provide monitoring of the large-scale changes in this region of Io [Phillips, 2000]. Because of the limited downlink and the desire to return more of the medium-resolution I25 data, only small portions of this low-resolution observation were returned. A 5-color rectangle over Loki and Daedalus Patera and a 3-color box over Pillan were played back.

These data did not conclusively show the presence of the 0.9 μm absorption feature at Loki but the signal-to-noise ratio was very low. More interestingly, the slivers of data from Pillan Patera provided hints that the red material on its floor changed to a greenish color [Phillips, 2000].

2.6. Orbit I27

This was the only fully successful Io orbit. However, it was also an orbit with little downlink allocated to remote sensing data. The problem was known before the I27 encounter with Io, but experience during I24 and I25 made it seem likely that a spacecraft anomaly would limit our data acquisition to something that could be played back. When the encounter was completed without mishap, the Galileo project modified its plans for orbit G28 to allow more of the I27 data to be returned to Earth. During the I27 encounter the G28 sequence was being re-planned to respond to the loss of summation mode imaging, a stuck grating on the Near-Infrared Mapping Spectrometer (NIMS), and other problems. It was found to be possible to save about 1/3 of the I27 data that was on tape for playback during G28. G28 was

<table>
<thead>
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<th>Table 8. Observations During E26</th>
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<tbody>
<tr>
<td>Observation</td>
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<tr>
<td>Number of Frames</td>
</tr>
<tr>
<td>Resolution (km/pixel)</td>
</tr>
<tr>
<td>Filters</td>
</tr>
<tr>
<td>Comments</td>
</tr>
</tbody>
</table>
Plate 2. Portions of, and interpretive products from, I25 observation GIANTS01. Cutout from raw image details the area where the image was bleeding. Red line indicates the location of the hot material that produced the bleeding, assuming that the hot area was only 1 pixel wide. North is to the upper left in the raw image. The lower color view shows the oblique I25 GIANTS01 observation reprojected with north to the top and combined with the orbit C21 color context data (violet, green, and 756-nm filters). The interpretive illustration attempts to show our best guess at the location of the hot lava and the style of volcanism: a 25-km-long fissure that had just begun to feed flows moving to the southeast. Also note the diffuse dark material expanding away from the source of the hot lava. This eruption is described in more detail by Wilson and Head [this issue].

Plate 3. Mosaic of I25 CULANN01 color observation. The observation used the violet, green, and red filters. Culann Patera is the small green depression surrounded by radial lava flows. The currently active flows appear black, with a narrow red-yellow line marking the lava tube that appears to feed the more distal ends of the flow field. Flows that were seen to be dark by the Voyager spacecraft in 1979 are now partially covered by diffuse yellow deposits. Bright red deposits surround Culann Patera indicating a plume rich in sulfur gases. However, the plume has proven difficult to image at visible wavelengths. Both the color of the deposits and the "stealthy" nature of the plume are characteristics shared with the much larger Pele plume. The mosaic also covers the northern part of Tohil Patera, which has a complex mottled pattern of colorful surface units. The convoluted margins of the boundaries between the color units are generally consistent with that of fluid lavas. The more diffuse boundaries between the green and brownish surfaces may indicate that they are the result of surface coatings of different lava units. The dark lavas are presumed to be fresh silicate flows, but the bright white patches are mysterious. Frozen sulfur dioxide flows are one possible explanation.
Table 9. Observations During I27

<table>
<thead>
<tr>
<th>Observation</th>
<th>Number of Frames</th>
<th>Resolution (km/pixel)</th>
<th>Filters</th>
<th>Comments</th>
</tr>
</thead>
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<tr>
<td>PELE1</td>
<td>4</td>
<td>0.017</td>
<td>CLR</td>
<td>Pele lava lake in the dark</td>
</tr>
<tr>
<td>SAPPNG1</td>
<td>4</td>
<td>0.0055</td>
<td>CLR</td>
<td>sapping scarp</td>
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<td>0.007-0.008</td>
<td>CLR</td>
<td>strip across Chaac</td>
</tr>
<tr>
<td>PROMTH1</td>
<td>8</td>
<td>0.011-0.013</td>
<td>CLR</td>
<td>strip across northern Prometheus flows</td>
</tr>
<tr>
<td>TOHIL1</td>
<td>4</td>
<td>0.165</td>
<td>CLR</td>
<td>stereo with I24 observation</td>
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<tr>
<td>PROMTH2</td>
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<td>0.170</td>
<td>756, GRN, VLT</td>
<td>color observation of Prometheus</td>
</tr>
<tr>
<td>CAMAXT1</td>
<td>12</td>
<td>0.180-0.185</td>
<td>CLR</td>
<td>regional mosaic over Camaxtli - Chaac region</td>
</tr>
<tr>
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<td>0.210</td>
<td>756, GRN, VLT</td>
<td>Amiran flow field, color over center</td>
</tr>
<tr>
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<td>0.315</td>
<td>967, 889, 756, VLT, CLR</td>
<td>color view of 125 lava fountain region</td>
</tr>
<tr>
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<td>6</td>
<td>0.335</td>
<td>CLR</td>
<td>near-terminator view of Zal region</td>
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<tr>
<td>SHMHHU1</td>
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<td>0.340-0.345</td>
<td>CLR</td>
<td>near-terminator view of Shamshu region</td>
</tr>
<tr>
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<td>0.350-0.355</td>
<td>CLR</td>
<td>regional mosaic of far south</td>
</tr>
<tr>
<td>GLOC0L1</td>
<td>12</td>
<td>3.1</td>
<td>756, GRN, VLT</td>
<td>hemispheric color</td>
</tr>
<tr>
<td>IOECLI1</td>
<td>2</td>
<td>17</td>
<td>967, CLR</td>
<td>eclipse</td>
</tr>
</tbody>
</table>

a very long orbit with a large amount of available downlink, allowing these deferred I27 images to be returned in their entirety.

The path of the spacecraft over Io during orbit I27 was similar but slightly to the north of the path during orbit I24 [McEwen, this issue]. It also provided good views of many of the same areas seen in I25. The science teams were able to persuade the minimally staffed sequence designers to modify the planned I27 observations in order to take advantage of the new discoveries made during C21-I25. The observations during orbit I27 are summarized in Table 9, and those aimed at volcanic targets are described in detail below. Other observations are detailed by Turtle et al. [this issue]. Some of these, especially the medium-resolution regional mosaics, contain a number of interesting volcanic features described by Radebaugh et al. [this issue].

2.6.1. PELE01. This observation was deemed necessary in order to confirm the puzzling I24 Pele observation and to avoid possible issues regarding the calibration of the garbled images. Again, Pele was in darkness but only four frames with long (48 ms) exposures were used. Galileo was lower and further to the north on I27, resulting in a marginally more oblique view. The images were returned with a 10:1 lossy compression to locate the hot areas, then two small windows were returned with lossless compression on the second pass through the tape.

The curving, glowing line seen at Pele in I27 is very similar to that seen in I24 (Figure 9). The western hot spots that were on the edge of the I24 frames are more clearly seen in the I27 observation. The limited bleeding seen at the brightest hot spots corresponds to a brightness temperature of ~1050 K, assuming that all the thermal radiation is from a single hot pixel filled with hot material.

2.6.2. CHAAC01. Chaac is one of the patera dubbed a “golf course” due to the green material on its floor. The primary goal of this observation was to provide <20 m/pixel images of the green material to help identify the processes that produce it. NIMS also detected a new hot spot at Chaac during I25, so we hoped for a chance to image active lava as well. However, due to the limited downlink available, only fragments of five frames could be played back (Figure 10). These fragments were scattered to provide snippets of both patera margins and a couple of samples of the central patera floor. Hot flowing lavas were not captured in these images.

Using shadow lengths from these high-resolution observations the northeastern scarp of Chaac Patera has been measured at 2.8 km. Scattered light from the floor of the patera weakly illuminates the upper portion of the scarp, showing it to be made of a series of near-vertical steps, much like the walls of calderas on terrestrial basaltic shield volcanoes [Radebaugh et al., this issue].

The albedo patterns within the floor of the patera suggest that a bright fluid has flooded low areas, much like at Tohil Patera. The imaged part of the southern margin of Chaac Patera is composed of a bright material that is incised by dark lobate streaks running down from fissures parallel to the margin of the patera.

2.6.3. PROMTH01. After the I24 observations the hypothesis that the Prometheus plume was the result of SO2 vaporized by advancing lava [McEwen et al., 1998a] was given quantitative attention. One of the suggestions from the theoretical study by Kieffer et al. [2000] was that the plume should have a 10 to 20-m-diameter vent within a larger crater.

Figure 9. Mosaic of a portion of the I27 PELE01 observation showing a curving line of hot lava glowing in the dark at Pele. The images have been reprojected with north to the top but no attempt has been made to filter the radiation noise that can be seen increasing toward the top of the mosaic. The size and shape of the curving line of hot material are almost identical to that seen in I24 (see Figure 3). The small hot spots seen to the southwest were also seen in I24. This shows that the thermal emission from Pele is tightly constrained geographically, suggestive of topographic confinement.
Plate 4. Color composite of the I27 TVASHT01 observation. This image is near true-color for the bulk of the area but uses the three infrared filters to highlight temperature differences across the active lava flows. This was accomplished by first making two separate mosaics: a “visible” mosaic using just the violet, clear, and 756-nm filters to synthesize what would be seen in violet, green, and 756-nm; and an “infrared” mosaic using just the 756-nm, 889-nm, and 968-nm filters. Then the portions of the infrared mosaic that showed glowing lava were simply cut out and pasted over the visible mosaic. For the hot lava, colors match relative temperatures with white being the hottest and orange being the coolest. However, because much of the lava was hot enough to saturate the infrared images, quantitative temperatures cannot be derived. The two bright spots at the northern end of the flow could be vents or the tips of advancing flows. The dark lava deposit at the I25 eruptive vent is remarkably similar to that of the interpretive illustration shown in Plate 2.

Plate 5. Interpretive map of the Prometheus region. The vent for the active flow field is presumed to be at the source of the red plume, ~15 km south of the newly discovered patera/caldera. The vent appears to be localized along a fissure that also serves as the fault marking the western boundary of the low mesa. The lava flows ~100 km westward under an insulating crust feeding a few smaller breakouts along the way. The majority of the active lava flows are concentrated in the “lava delta” at the western end of the flow field. The interaction between these active flows and the sulfurdioxide-rich substrate appear to produce the visible plume [e.g., Milazzo et al., this issue].
Figure 10. The isolated partial frames from I27 observation CHAAC01 with context frame from I27 observation CAMAXT01. The resolution jump from ~8 to ~180 m/pixel between the high-resolution "postage stamps" and the context image is large enough to make it difficult to accurately position the high-resolution data. The two northern frames show parts of the patera wall, showing the striking difference in texture of the material outside and within the patera. The hummocky material appears to be part of a mountain or mesa while the patera floor appears to be inflated and ponded lavas. Shadow measurements indicate that the wall of the patera is >70° [Radebaugh et al., this issue]. The light colored patches on the patera floor appear to fill low areas within the lava flow, suggestive of a bright, low-viscosity liquid seeping through the flow after it had solidified. Sulfur-rich liquids are the most likely candidate for this fluid. The southernmost frame shows a deep pit that may be a vent that lava has drained back into, much as at the 1959 Kilauea Iki eruption [Eaton et al., 1987]. It is interesting that this portion of the southern wall of Chaac patera is bright. Dark material is seen exposed downslope from the fractures along the wall. This could conceivably be dark, fissure-fed lava moving over a sulfurdioxide rich slump deposit.
The I24 high-resolution observation did not identify such a crater but only covered the southern half of the Prometheus flow field. Thus, the primary goal of this I27 observation was to image the remaining area from which the plume could be erupting. While the conduit that the gas was erupting from might only be a pixel in size, we expected a significantly larger vent structure surrounding the hole.

Because of pointing errors, the entire observation was shifted north by about 1/3 of a frame and east by about a frame. The first four frames of this observation were returned during I27, and the remaining four frames have been returned during G28. The images have been played back with 3.6:1 – 7.4:1 lossy compression. The offset pointing of the observations means that the most likely candidate location for a vent for the Prometheus plume is still not imaged at high resolution. However, bright streaks are seen emanating from where the active flows run into the surrounding plains. The bright material escaping from the front of the lava seems to plaster the sides of the ridges in the plains [Milazzo et al., this issue]. Some of these bright patches saturated the detector, indicating very high albedos (~1.0).

Small, kilometer-scale dark lobate patches produce a quiltwork pattern over the lava flow field, especially on the western end. These dark patches are interpreted to be very recent lava flows, with surfaces too hot (or too young) for significant accumulation of significant SO₂-rich plume deposits. The margin of one dark patch seen in the middle of the flow field has small very bright spots. These are interpreted to be incandescent lava.

2.6.4. PROMTH02. As previously noted, the problems with summation mode imaging during I24 largely eliminated any useful color information in the I24 PROMTH02 observation. This I27 observation was to recover these data. While only a small rectangle of one of the green filter images was returned in I27, the remainder of this observation was played back during G28. The color mosaic is shown by Milazzo et al. [this issue].

In addition to providing context for the high-resolution PROMTH01 observation, changes are visible between the green frame of I27 PROMTH02 and the relatively ungarbled portions of the green frame of the I24 PROMTH02 observation [McEwen et al., 2000]. The color data returned to date show a fan of bright streaks emanating from the front of the flow field. Similar streaks were visible in the earlier images of Prometheus, but their position seems to change from observation to observation. No evidence of a central plume vent has been found [Milazzo et al., this issue].

2.6.5. CAMAXTO1. This is a regional mosaic covering the area from Chaac Patera to Camatlii Patera. A number of additional active paterae are located in this region, surrounded by what appeared at low resolution to be smooth plains. Only a portion of the frame over Camatlii was returned in I27, but all of this observation was returned during G28. The entire observation, combined with C21 color data, is reproduced by Radebaugh et al. [this issue].

The context frame for the high-resolution CHAAC01 observation shows that the dark portion of Chaac Patera is part of a much larger set of depressions. The easternmost of these depressions is exceptionally white and NIMS spectra suggest that it is relatively pure SO₂ [Lopes et al., this issue]. The surrounding plains are all covered with kilometer scale hummocks/flutes. Scarps seen within the plains indicate that Chaac Patera is cut into a low mesa. The Chaac and the other calderas seen in this observation are discussed in more detail by Radebaugh et al. [this issue]. A preliminary geologic map is presented by Williams et al. [2001].

2.6.6. AMRANI01. As noted earlier, while the I24 regional mosaic over the Amirani-Mau region was generally reconstructable, the frames covering Amirani itself were especially hard hit. This observation was to recover the missing part of the I24 regional mosaic and add color information. Due to the limited tape available, this observation was limited to a 1x3 strip of green filter images over the main Amirani flow and a violet and a 756-nm filter frame over the middle of the flow.

This observation answers some of the key questions about this immense flow field, but it deepens other puzzles. The flow field is clearly composed of many smaller flows, making it a compound flow field. When compared to the C21 context images, several new dark areas, interpreted to be fresh lava, are visible near the northern end and central part of the flow field. These are remarkably similar in form to the breakouts visible on Prometheus, and appear to emanate from a series of sources within the flow field. Each one of these "small" breakouts is similar in size to the entire current Kilaeua flow field. Jets and halos of bright material surround the front of the dark breakouts where they extend into the surrounding plains. A possible vent for the main Amirani plume is seen as a dark spot a few kilometers across near the southern end of the flow field. The lava in this area is largely obscured (presumably the airborne and fallen plume deposits) but some dark flows can be seen extending radially away from the plume vent. At this resolution, the red lineament and patera just south of the Amirani flow field do not have any obvious association with the lava flow, but NIMS data indicate that it is warm [Lopes et al., this issue]. The bright red linear feature may have been shaped by tectonic forces rather than being a primary volcanic feature.

2.6.7. TVASHTO1. The most stunning image from I25 was that of active lava fountaining in Tvashtr Catena. The I27 observation was to provide 5-color data over the new lavas in order to search for the ~0.9 μm absorption feature seen on some Ionian lava flows. In most regions the lava is rapidly coated with sulfurous compounds, obscuring the spectrum of the lava itself. A high-resolution color image of this very fresh lava provided our best opportunity to search for this spectral feature. Ground-based telescopic observations led us to expect the eruption to be over by I27, so we also hoped to see the final morphology of the products from a short-lived, fissure-fed eruption on Io. The violet, 756-nm, and clear filter images were returned in their entirety with 2.3-4.3:1 lossy compression. Slivers of the 889-nm and 968-nm filter images were played back on the first pass through the tape, allowing small cutout windows centered on the recent lavas to be played back on the second pass.

Once again, Tvashtr provided a surprise with a display of active lava flows. Plate 4 shows the color composite image using the three near-infrared filters to visualize the thermal emissions from the lava. The active lavas are in the depression to the northwest of the depression where the active fissure was seen in orbit I25. It is not clear if the active lava flows seen in I27 are part of a separate eruption or are the continuation of the activity seen in I25. Large portions of the infrared images are saturated, making it impossible to provide precise temperatures. The data require a brightness temperature >1175 K, but lava temperatures are probably much higher. It is also interesting to see that the effusive and pyroclastic deposits from the Tvashtr eruption appeared to be recoating similar albedo materials. There was no dramatic difference in the appearance of the area around the I25 eruption between orbits C21 and I27.

2.6.8. SHMISHU01. The region surrounding Shamshu Patera has a number of intriguing mountains and paterae. This
observation was aimed at gaining a better understanding of the association between tectonic and volcanic features. It is discussed in more detail by Turtle et al. [this issue] and Radebaugh et al. [this issue].

However, we make note of one purely volcanological objective of the observation: the search for the site of the thermal “outburst” seen in August 1999 by ground-based telescopic observers. The thermal output from this eruption was marginally greater than that from Tvashar, suggesting the possibility of dramatic surface changes [Howell et al., this issue]. Three different (unnamed) paterae were considered likely candidates for the site of this eruption. One of these had been imaged in I25 and did not seem to be active at that time. To our disappointment, neither of the other two paterae that were seen in SHMSHU01 showed dramatic evidence of recent volcanism either. While small fresh-looking dark flows were visible in these paterae (up to 90 km² in area), there was no evidence major changes in their shapes since orbit C21. It is plausible that, like at Tvashar, the new flows have covered earlier dark lavas. More ephemeral eruption products, such as thin blankets of pyroclastic materials might never have been produced by this eruption or had faded between August 1999 and February 2000. More recent analysis of the telescopic data now suggests that Gish Bar Patera was the likely source of the outburst [Howell et al., this issue].

2.6.9. GLOCOLO1. This was a global color observation at low resolution over the hemisphere centered on Pele and Pillan. While an important observation for monitoring the large-scale changes on Io, it was primarily included in case the high-resolution imaging was again lost. Because all the high-resolution data were successfully acquired, we only played back a tiny fragment of this observation to provide a color view of the changes at Pillan.

2.6.10. IOECL101. This was another low resolution observation to continue the monitoring of Io at a global scale. However, due to the limited downlink, only a sliver of these data were returned.

3. Interpretation

The interpretations of the observations from several of the volcanic centers are detailed in other papers in this special section. The following discussion only provides a general overview of the type of activity seen at a few of the best studied volcanic centers. These interpretations are necessarily preliminary, and any discrepancies between the different interpretations given in the different papers in this special section should provide a clear warning that much of Io remains a mystery that the new data have only deepened.

NIMS has provided a whole additional dimension to the high-resolution Io data by extending our view into the infrared [Lopes et al. this issue]. The co-analysis of the NIMS and SSI data from Pele and Pillan by Davies et al. [this issue] is providing a much improved understanding of the temporal evolution of these two intriguingly different volcanic centers on Io. Modeling of the lava flows at Pillan also provides new constraints on the eruptions of high-temperature lavas on Io [Williams et al., this issue (b)]. The much studied plume at Prometheus is reexamined in the light of the new data by Milazzo et al. [this issue]. The possible sulfur flows at Emakong are described and modeled by Williams et al. [this issue (a)]. The eruption seen in I25 at Tvashar is modeled by Wilson and Head [this issue]. The various paterae are described and discussed by Radebaugh et al. [this issue].

3.1. Pele

The temporal evolution of the thermal signature at Pele is indicative of a stable, long-lived lava lake [Davies et al., this issue]. The high-resolution images from SSI support this idea. The size, shape, and temperatures seen at Pele are very similar between I24 and I27, indicating that these areas where hot lava is exposed to the surface did not migrate even ~100 m over a few months.

The curving hot area has been tentatively interpreted as the active margin of the lava lake. The PPR measurements at 17 µm suggest that the surface to the west of the glowing line is cold and the area to the east is warm (>150 K) [Spencer et al., 2000a]. This would be consistent with the glowing line seen by SSI corresponding to the SW margin of a lava lake. The thermal modeling of Carr [1986] suggests that it would take of the order of 10 years for a basaltic lava surface to cool to ~170 K and the crust would be >10 m thick. We speculate that the bulk of the Pele lava lake has a thick, stable crust that is only broken up along the margin of the lake where the crust is pushed against the patera walls. The I27 NIMS observation shows what appears to be hot material spreading away from a central line, again consistent with a long-lived lava lake. However, this NIMS observation is inconsistent with the hot material being exposed only along the margin of a lava lake. This would suggest that NIMS and SSI have imaged different parts of the Pele lava lake.

The relatively low level of thermal emission seen by SSI could be the result of (1) the spacecraft flying past the hottest areas, (2) the hottest areas hiding within a deep pit, or (3) the hottest areas lying outside the camera’s field of view. The spacecraft booms were expected to obscure about 1/3 of the images, making it exceedingly unlikely that large hot areas were missed in the I24 short exposure, the I24 long exposure, and the I27 long exposure mosaics. The idea that the hot material is hiding in a deep hole can be rejected because the I27 NIMS observation that saw substantial thermal emission was collected only a few tens of seconds before the SSI image. While the viewing geometry changes rapidly near closest approach, spacecraft motion is not adequate to have such a large hot area disappear so suddenly.

The actual explanation seems to be that we missed the hottest parts of Pele simply because the camera was pointed at the wrong place. Review of the imaging commands shows that, when the NIMS instrument saw the largest hot area, it was commanded to look to the south and east of the SSI fields of view. The glowing line seen by SSI appears to be just the westernmost edge of the main hot feature seen by NIMS [Davies et al., this issue].

3.2. Pillan.

Pillan is the site of the largest new eruption witnessed by Galileo and the location of the best evidence for high temperature lavas on Io [McEwen et al., 1998a, 1998b; Davies et al., this issue]. As such, Pillan has attracted special interest and is examined by Williams et al. [this issue (b)] and Davies et al. [this issue]. On the basis of the NIMS data, it is possible to constrain the start of the Pillan eruption to be shortly before orbit G8 (May 7, 1997), and the level of activity was seen to steadily decline after orbit C9 (June 18, 1997) [Davies et al., this issue]. From the thermal output, the Pillan eruption was thought to involve rapid, possibly turbulent, emplacement of poorly insulated lava flows [Davies et al., this issue; Williams et al. this issue (b)].

The SSI images provide direct observations of the style of eruption at Pillan [Williams et al., this issue (b)]. A ~40-km-long, northwest-southeast oriented, fissure system served as the
vent for the lava. The fissure(s) are the continuation of the extensional fractures seen in the mountain directly north of Pillan Patera, indicating a close connection between the mountain building tectonics and volcanic eruptions. These fissures are also marked by a streak of diffuse red material [Phillips, 2000]. Similar red material surrounding Pele forms from plumes shown to be rich in S$_2$ gas [Spencer et al., 2000b]. From the fissures, most of the lava flowed in two ~50-km-long arms extending to the east and southeast. The southeastern arm dumped lava into Pillan Patera in three places. The C10 and E11 eclipse observations show two distinct hot spots at Pillan. These correspond to the hot lava exposed at the vent and where the flows cascaded over the rim of Pillan Patera. The flow was partially insulated between the vent and lava falls, probably by a disrupted crust formed on active channels.

The lava channel seen in the highest resolution (124) view of the Pillan flow field could be constructional features or locations where the ultrabasic lava has incised into the volcanic-rich plains. Such thermal erosion is modeled by Williams et al. [this issue (b)]. The mysterious pits in the high-resolution images appear to have formed by explosive venting of gasses. As such, they could be the southern end of the fissure vent that fed the Pillan lavas and could have formed by the explosive eruption of the volatilized substrate blasting through the lava. Kieffer et al. [2000] described how such a process (analogous to rootless cones on Earth) could form plumes on Io. Unfortunately, without intermediate-resolution context images the detailed morphology of the Pillan flow field may forever remain a mystery.

Examining the C10, E14, and E26 SSI images, it is possible to measure area coverage rates: 3100 km$^2$ of new lavas appeared by C10 and the floor of Pillan Patera (an additional 2500 km$^2$) was covered between C10 and E14. Williams et al. [this issue (b)] estimate the flow thickness to be of the order of 10 m, indicating a total of about 56 km$^3$ of lava. The pyroclastic deposits covered over 100,000 km$^2$, but the thickness of this deposit is unknown. On Earth, vigorous basaltic eruptions can convert ~10% of the erupted volume into pyroclastics [e.g., Thordarson and Self, 1993]. If this can be transferred to Io, the pyroclastics could make up ~5 km$^3$, and the average pyroclastic deposit thickness could be as much as several centimeters.

Williams et al. [this issue (b)] and Davies et al. [this issue] use various temporal constraints and thermal models to estimate eruption rates. Both studies produce numbers in the thousands of cubic meters per second, similar to the most vigorous eruptions recorded on the Earth. However, peak rates could be significantly above these average rates. If the platy lava morphology seen in the I24 high resolution image is real, and if it formed in the same way as platy lavas seen in high-resolution images of Mars [Keszthelyi et al., 2000], then eruption rates as high as $10^4$ m$^3$ s$^{-1}$ might be expected during the most vigorous part of the eruption.

The improved temperature constraints, and the implications for lava composition and material properties, are discussed at length by Davies et al. [this issue] and Williams et al. [2000, this issue (b)]. The rate at which the various Pillan deposits are being modified is detailed by Phillips [2000]. Particularly intriguing is the observation that the red Pele plume deposit landing on the warm lavas inside Pillan Patera has turned green over a few months.

3.3. Zamama

The distributions of lava flows around Zamama suggest that it is a shield volcano with a central vent and a rift zone. The large dark flow field, which appeared between the Voyager flybys and Galileo’s orbit G1, seems to have been fed from the rift zone. The flow field changes from a series of narrow finger-like flows into a broad sheet as it extends away from the vent. This is most likely to be the result of the change in slope from the flanks of the volcano onto the surrounding plains. The lack of discernible surface features on the large flow field suggests that it is an evenly inflated sheet flow, but the garbling and reconstruction of the images may have hidden interesting features.

In contrast to the main flow field, the flows emanating from the central vent are brighter in color. This could be the result of either a sulfurous lava composition or silicate lavas coated by sulfurous deposits. Thermal erosion into a sulfurous substrate is much more likely if the lavas were silicate, so the composition(s) of the lavas erupting from the top and the flanks of the volcano remain enigmatic.

The main visible (bright) plume was seen erupting from the center of the main dark flow field. The E14 image of Zamama shows diffuse plume deposits extending away from a linear source 20-30 km long. However, the red diffuse material, presumably rich in short-chain sulfur, emanates from the central vent of the shallow shield edifice. The red material is blown radially away from the main (bright) plume. This suggests that the gas pressure generated by the “red” plume is significantly lower than that of the bright plume.

The apparent shutdown of the Zamama plume between orbits E14 and C21 suggests that this eruption may be coming to a halt. However, there has been no observation of the Zamama hot spot by SSI since orbit E11, so we do not have the data to determine the relationship between thermal output (presumably closely related to lava output) and plume activity.

3.4. Chaac

The primary objective for imaging Chaac Patera was to observe the mysterious green floor at high resolution. The observation clearly shows that the floor of Chaac Patera is covered with lava. However, these panchromatic images cannot directly show whether the green color is a primary feature of the lava or if it is the result of a secondary coating. Instead, as described in the next section, the medium-resolution color observation of Culann and Tohil Paterae provides more information about the formation of green surfaces. NIMS spectra, however, do provide important clues to the composition of the surface [Lopes et al., this issue].

The lavas within Chaac have morphologies remarkably similar to those found within typical basaltic shield volcano calderas such as Kilauea Caldera, Hawaii. This is not surprising since lavas have a strong tendency to pond and/or inflate when they are as topographically confined as they are in terrestrial calderas and Ionian paterae. The draining of lava back into the vents is also common in Hawaiian caldera/crater eruptions, typically resulting from the loss of volume when the gas phase separates from the erupting magma [Eaton et al., 1987]. The presence of drained ponds and deep pits suggests that Ionian lavas may undergo a similar process. This could imply that some Ionian lavas have a significant gas fraction when erupting. Such a gas phase would play a key role in driving dense, basic/ultrabasic magma up from depth. These same processes would propel the liquid silicate droplets thought to make up the dark pyroclastic deposits surrounding many eruption sites.

There are also distinct differences between Chaac Patera and most terrestrial basaltic calderas [Radebaugh et al., this issue]. For example, in Chaac, lava rises along rim fractures. In Kilauea
and many other terrestrial basaltic calderas the lava erupts from fissures that are able to cut across the floor of the caldera. This observation supports the idea that many Ionian paterae could be formed by the interaction of volcanism and extensional tectonics [Jaeger et al., 2001]. The magma rises along the extensional fractures that mark the boundary between the surrounding plains/plateaus and the floor of the caldera can be a pull-apart basin partially filled with lava. The term “volcano-tectonic depression” is more appropriate than “caldera” to describe this kind of patera. We speculate that many paterae are opened by extensional tectonics and the shapes of the depressions are heavily modified by intrusions and extrusions mobilizing near-crust volatiles.

The mottled albedo patterns on the floor of Chac 3.6 Patera appear to be tumuli and lava-rise pits diagnostic of inflated flows as well as perched “bathub rings” and stranded islands indicative of deflated lava ponds. This suggests that the floor of Chac 3.6 Patera has been covered by a combination of lava flows and lava lakes, some of which have drained back into their vents. A pit that could be both the source and sink for a lava pond is visible in the southernmost frame of the observation.

The high-albedo materials on the floor of Chac 3.6 Patera seem to be a bright, low-viscosity fluid seeping into depressions within the lava. This could plausibly be an SO₂-rich liquid. The heat and pressure of the overlying lava could convert solid SO₂ to the liquid state, allowing it to flow through the permeable solidified lavas. When the liquid SO₂ reaches the surface, it will want to vaporize. However, the process of vaporization must remove a large amount of heat from the liquid, allowing a solid insulated crust to form. A comparison to lava flow models suggests that SO₂-rich liquids should easily flow hundreds of meters. Similar processes have been evoked to produce ice-covered streams and lakes of water on Mars [e.g., Carr, 1983]. Further discussion of evidence for SO₂-rich fluids on the surface of Io are discussed by Turtle et al. [this issue], Moore et al. [this issue], and Lopes et al. [this issue].

3.5. Culann

The medium-resolution color observation over the Culann region provides our most detailed look at the relationships between different color units on Io. At both Culann and Tohil, the green materials are confined to the lava flow surfaces that are being covered by red material. We speculate that a reaction between the red plume deposits (rich in unstable short-chained sulfur) and the warm lava produces some green sulfur compound. Kargel et al. [1999] suggest iron as the contaminant that transforms the elemental sulfur in the plume deposits to a green color. However, this is not consistent with NIMS spectra of other green areas [Lopes et al., this issue]. While the yellow areas could be less contaminated sulfur, we currently have no explanation for the reddish brown lavas on the eastern end of Culann.

The multicolored sinuous linear feature on the active Culann lava flow field is interpreted as a lava tube system with a roof that has been discolored by volcanic gasses and is feeding a series of small distal breakouts. The long dark lava flows extending northwest from Culann Patera have formed a compound, tube-fed flow field. Lava flows in a similar orientation were visible in the 1979 Voyager images of Culann. However, careful comparison of the Voyager and Galileo images show that the distal half of the dark lavas has shifted to the north [Phillips, 2000]. The fact that only the distal half of the flow field has moved strongly suggests that lava has been flowing through the proximal half of the flow field since at least Voyager times. While >20 years seems long for a single lava flow to be active, on Kilauea, sections of individual lava tubes have been seen to remain active for >3 years [Kauahikuaa et al., 1998] and other tube systems have been inferred to have been active for ≥20 years [e.g., Keszthelyi and Pieri, 1993].

3.6. Prometheus

The interpretation of the Prometheus flow field as a long-lived, tube-fed, compound pahoehoe flow field is described in some detail by McEwen et al. [2000]. A small diffuse red plume that emanates from just south of the Prometheus patera corresponds to a small but intense NIMS hot spot and is likely to be the vent for the silicate lavas [Lopes-Gautier et al., 2000]. It is interesting that the vent is not within the caldera-like depression but is instead along what appears to be a tectonic boundary. Plate 5 is a geologic sketch map of the Prometheus region.

Other than a small active breakout midway down the flow field (with incandescent lava imaged in the 127 high-resolution mosaic), no hot lava is exposed until it reaches the western end of the flow field. In fact, a portion of the flow field is cold enough to be covered by a thick layer of plume materials that locally obscures all lava features. Such insulating transport must be in tubes or sheets with thick roofs.

The wide distribution of breakouts in the western part of the flow field suggests either an intricate network of tubes or a set of broader sheets of melt. The morphology of the individual breakouts, with lava spreading in many directions at once, indicates very shallow slopes. On such shallow slopes, terrestrial flood basalts have formed broad sheet flows rather than discrete lava tubes [Keszthelyi and Self, 1998]. This suggests that the slopes in the proximal parts of Culann are significantly larger than the slopes in the distal part of the Prometheus flow field.

Comparing the 124 and 127 medium resolution images, it is possible to see that ~60 km² of new dark lavas have formed and a similar amount of previously dark lava has faded. This corresponds to an areal coverage rate of about 0.5 km²/day or 5 m² s⁻¹ [McEwen et al., 2000]. While this is approximately 10 times higher than the areal coverage rate of the current Kilauea eruption [Mattson et al., 1993], it is ~7 times less than the rate estimated from thermal modeling of the earlier low-resolution NIMS data [Davies et al., 2000]. This discrepancy could be explained by either (1) the production of new lava at Prometheus being significantly lower between orbits 124 and 127 than during 1996-1997, (2) the earlier low resolution NIMS data contains the thermal output from other volcanic activity, (3) some unknown limitation of the thermal modeling or (4) the production and burial of dark lavas takes place on a timescale much shorter than the 134 days between 124 and 127. As explained below, we have reason to suspect that the output of lava has been remarkably constant at Prometheus. With increased spatial resolution, the complexity of processes at different Ionian volcanic centers is becoming evident and the NIMS data is being more effectively modeled [e.g., Davies et al., this issue]. The validity of the thermal models is being tested by application to well-studied terrestrial eruptions for which similar remote sensing data is available [Keszthelyi et al., 2001]. It is quite likely that the compound nature of the flows at Prometheus produce less areal coverage than the thermal models would predict.

Perhaps the most studied aspect of Prometheus has been its long-lived, bright plume. While originally assumed to be forming over the vent for the silicate lavas, the new high-
resolution SSI images corroborate the suggestion of McEwen et al. [1998a] that the plume forms over the active flow front. Kieffer et al. [2000] provide a relatively simple model of how a thick lava flow can melt and vaporize a large volume of SO$_2$-rich substrate that then blasts through the overlying lava. Kieffer et al. [2000] envisioned that all the SO$_2$ volatilized by the western end of the Prometheus flow field would be erupted through a single 10 to 20-m-diameter choked vent. A single, well-established conduit for the plume was assumed necessary to explain the constancy of the Prometheus plume’s dimensions and brightness.

However, the most recent 127 high-resolution images of the Prometheus lavas clearly show bright materials erupting from several points along the flow front. Detailed examination of the medium-resolution context images also suggests that the plume has a diffuse source [Milazzo et al., this issue]. As noted earlier, the bright Zamama plume also seemed to have an extended source region. These observations, and thermal modeling of mafic lavas moving over an SO$_2$-rich substrate, have led Milazzo et al. [this issue] to propose that there is no central plume vent at Prometheus. The constancy of the plume would be the result of a steady output of fresh lava, not the fixed geometry of the plume vent.

3.7. Amirani

The Amirani-Maui flow field includes the longest active lava flows known in our solar system. The ~300-km-lengths of the flows compares favorably with the largest flows documented on the Earth (in the Columbia River flood basalt province) as well as long flows on the other planets. Several statements can now be made more confidently about the Amirani-Maui flow field. First, these flows are undoubtedly fed by insulating tubes or sheets because high thermal emission is limited to a few discrete spots along the flow field [Lopes et al., this issue]. They also are clearly forming a complex, compound flow field. Because it has been seen to be active in the Voyager data and throughout the Galileo mission, it seems very likely that Amirani has been active for at least 20 years. These observations are consistent with the model for terrestrial flood basalt emplacement suggested by Self et al. [1997] and Thordarson and Self [1998].

By comparing the observations of Amirani taken during orbits 124 and 127, it is possible to quantify the area covered by new lava in the intervening 134 days (Plate 6). The ratio image shows 23 distinct new breakouts, covering a total of ~620 km$^2$. By comparison, Kilauea covered only ~10 km$^2$ and Prometheus ~60 km$^2$ in the same time. Despite its size, the total effusion rate implied by the coverage rate at Amirani is very moderate. Assuming a flow thickness of 1-10 m, the eruption rate is only 50-500 m$^3$ s$^{-1}$. These eruption rates are significantly lower than the ~4000 m$^3$ s$^{-1}$ suggested by Thordarson and Self [1998] for similar sized Columbia River flood basalt flows on the Earth. In fact, they are only slightly higher than the minimum eruption rates needed to form tube-fed lava flows 300 km long [Keszthelyi, 1995].

Perhaps the biggest remaining puzzle at Amirani is where the lava comes to the surface. The current plume site is an excellent candidate, based on the fact that all the flows seem to extend away from this point. However, in most cases bright red material is associated with the primary silicate vent. The red patera and fracture to the south of the flow field are both warm and could be the main vent, but this would require all the lava to flow through the very narrow (~500 m wide) tip of the linear fracture.

3.8. Tvashtar

The intensely glowing flows at Tvashtar Catena may well be some of the most visually spectacular discoveries of the entire Galileo mission. The 125 lava is interpreted as a lava fountain. The hot material generally follows the margins of a small patera. This would allow the lava to be either a flow confined against the edge of the patera or a fissure opening along the patera-bounding fault. However, because the hot material extends well above the floor of the patera (Plate 2) the preferred interpretation is that the lava is being thrown upward to an elevation ~1 km. Fountaining of lava along a long fissure is commonly called a curtain of lava.

Sudden infrared brightenings of Io seen by ground-based astronomers had been previously interpreted to be fountains of very hot silicate lavas [e.g., Davies, 1996; Stansberry et al., 1997]. The ground-based monitoring also indicated that such spectacular volcanic displays were both rare (seen in 3.3±1.5% of the observations) and short-lived [e.g., Howell et al., this issue]. Given the small fraction of Io that Galileo could image at moderate to high-resolution, and the long lead times needed to plan the imaging sequences, we never expected to be able to image such an event.

The SSI observations of Tvashtar Catena corroborate the earlier interpretation of the ground-based observations, giving us much greater confidence in our ability to interpret the volcanic activity on Io from such low spatial resolution monitoring. Other aspects of the eruption fit well with our observations at other volcanic centers. For example, the active fissure was along one of the margins of a patera, again showing an interplay between volcanism and tectonism. The diffuse dark halo deposited around the fissure appears to be a smaller version of the ash deposit surrounding the Pillan eruption site.

Also hard to explain is the morphology of the active flows seen in the 127 color image. The new lavas cover nearly exactly the same area as an earlier dark lava flow. This could be the result of topographic confinement, but the scarps must be quite low because they are not visible in the 180-200 m/pixel images. The direction the lava is flowing is also a puzzle. One interpretation is that the lavas are fed from the south, producing a large warm sheet near the vents, cooler insulated sheets farther to the north, and small incandescent spots mark the advancing flow front. However, this would require that the advancing lava front at the time of the 127 image to be coincident with the maximum extent of the older flows. If the extent of the flows was being halted by topography, a bright spot would not be expected at the distal end of the flow. Instead, most lava flows advance across a wide flow front, so we would expect a broad hot region on each advancing flow.

The alternative is that the lavas are fed from two vents (the small discrete hot spots to the north and northwest). The crust of the lavas in the proximal area then would have had an opportunity to cool below the detection limit of SSI while the entire medial-distal section of the flow is still glowing. To have such a broad area still hot, either the lavas were very recently emplaced or the crust is being destroyed and renewed as the flow advances. Since SSI can only detect thermal emissions from lavas that are minutes old, for the first explanation to be valid, the lava flow would have to have advanced tens of kilometers in minutes (i.e., flow velocities of ~100 m s$^{-1}$). Given the apparently flat floor of the patera, such high flow velocities seem unreasonable. It seems more likely that the lava is an open sheet flow that is being fed by two separate vents, both of which are located along the margins of the patera.
Plate 6. Changes at Amirani between I24 and I27. The color image on the left is a composite of 210 m/pixel I27 green filter images and 1.3 km/pixel color data from C21. The white boxes and arrows show the locations of the areas analyzed in detail on the right. The left-hand pair of black and white images are parts of a 500 m/pixel I24 AMSKIGI mosaic taken in the clear filter. The center pair of image are I27 data taken in the green filter. The right-hand pair of images are produced by dividing the I24 data by the I27 data. The new lava is shown in red. The changes in albedo associated with the appearance of new dark lava are sufficiently large to override the different responses of the green and clear filters, but more subtle variations in the ratio image may not reflect actual changes at Amirani. Also, the increase in resolution between the I27 and I24 data introduces some artifacts around the edges of sharp albedo contrasts. The ratio image shows about 620 km$^2$ of new lava spread over 23 separate breakouts.
4. Discussion and Conclusions

The new data from Io demonstrates that each and every volcanic center is unique. There is a wide range of eruption rates and lava morphology. Despite the many oddities, some very broad generalizations can be drawn. The majority of Ionian eruptions can be placed in two classes that we call “Promethean” and “Pillanian.”

Examples of Promethean eruptions include the current activity at Prometheus, Culann, Zamama, and Amirani. These volcanic centers have long-lived, compound flow fields fed by insulated lava tubes or sheets. The lengths of the flows can be hundreds of kilometers and the morphology of the flows is suggestive of pahoehoe. Eruptions seem to be able to continue for at least 20 years. Lava temperatures obtained to date are consistent with basallic compositions [Lopes-Gautier et al., 2000], but ultrabasic compositions have not been excluded. These eruptive centers generally correspond to the “persistent” hot spots described by Lopes-Gautier et al. [1999].

Examples of Pillanian eruptions are Pillan and Tvashtar. While the initial Tvashtar deposits were dwarfed by the scale of the Pillan eruption, it shares several key characteristics: a short-lived intense episode with high-temperature, fissure-fed eruptions producing both extensive pyroclastic deposits, and rapidly emplaced lava flows with open channels or sheets. These vigorous eruptions expose large amounts of liquid lava, providing a much better opportunity to remotely estimate lava temperatures than at Promethean eruptions. These types of eruptions correspond well with the occasional “outbursts” seen by ground-based telescopic observers [e.g., Stansberry et al., 1997; Howell et al., this issue]. To date, reliable very high lava temperatures have only been derived from Pillanian/outburst activity [e.g., Blaney et al., 1995; Stansberry et al., 1997; McEwen et al., 1998b]. However, it is possible that after an initial Pillanian phase, an eruptive center could switch to a Promethean style of eruption.

Of course, there are volcanic centers that do not fit either category. Pele is a long-lived eruptive center, but the lava does not seem to be able to form extensive flows. Loki has some of the most energetic outbursts on Io with inferred massive floods of lava, but has not produced extensive pyroclastic deposits (that we have been able to detect).

There are also generalizations that appear to apply to all Ionian eruptions. The 100-km-scale bright plumes (Prometheus-type plumes of McEwen and Soderblom [1983]) generally form over the distal ends of extensive flow fields. These plumes do not mark the vent for the silicate lavas and seem to be the result of the hot lavas volatilizing the SO₂-rich substrate.

Previously, from lower resolution observations it was possible to see a correlation between red diffuse materials and active silicate eruptions. Now, with higher resolution observations, it appears that the red materials are being produced at the vents for silicate lavas. The red material is most likely to be short-chained sulfur, suggesting that sulfur is an important component of the magmatic gasses. The presence of unoxidized sulfur in the magmas places important constraints on the oxygen fugacity of the magmas [e.g., Zolotov and Fegley, 1999, 2000].

There is also a growing realization of the degree to which tectonism and volcanism affect each other on Io [Turtle et al., this issue; Radebaugh et al., this issue; Jaeger et al., 2001]. Most of the eruptions of silicate lavas appear to be fed from fissures that are also tectonic fractures. In many cases these same fractures appear to play a key role in the formation or modification of mountains. Furthermore, a number of the paterae on Io may be volcanically modified tectonic basins rather than classic calderas.

It is worth ending with a note of some of the features we did not find. There continues to be a lack of evidence for evolved (high viscosity) lavas on Io. Only the two enigmatic tholi imaged by Voyager remain candidates for more evolved lavas.

The evidence for sulfurous volcanism is also surprisingly weak. The problem may be that flows with temperatures appropriate for liquid sulfur cannot be detected by SSI and can be mistaken for cooling silicate flows in lower resolution NIMS data. Inactive lava flows that have yellow colors could either be sulfur flows or be silicate flows with a thin veneer of sulfurous compounds. The bright low-viscosity flows seen within Chac and Tohil Paterae suggest that SO₂-rich fluids might also flow for short distances on Io’s surface. The relative proportions of silicate and sulfurous compounds in the crust of Io remains an unresolved question.

Ultimately, the compilation of NIMS, PPR and SSI data, such as presented by Davies et al. [this issue], will probably be the key to deciphering Io’s volcanoes. Combined with the insights provided by examination of the global tectonics, new geophysical data, and improved physical modeling, we hope to achieve a new understanding of the interior of Io over the next several years.

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