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The Pele plume (Io): Observations with the Hubble Space Telescope

John R. Spencer,[1] Paola Sartoretti,[2] Gilda E. Ballester,[3] Alfred S. McEwen,[4]
John T. Clarke,[3] and Melissa A. McGrath[5]

Abstract. In July 1996, with the Hubble Space Telescope (HST), we observed the Pele plume silhouetted against Jupiter at a wavelength of $0.27\mu m$, the first definitive observation of an Io plume from Earth. The height, 420 ± 40 km, was greater than any plume observed by Voyager. The plume had significantly smaller optical depth at 0.34 and $0.41\mu m$, where it was not detected. The wavelength dependence of the optical depth can be matched by a plume either of fine dust, with minimum mass of 1.2×10^9 g and maximum particle size of $0.08\mu m$, or of SO_2 gas with a column density of 3.7×10^{17} cm^{-2} and total mass of 1.1×10^{11} g. Our models suggest that early Voyager imaging estimates of the minimum mass of the Loki plume [*Collins*, 1981] may have been too large by a factor of ~ 100. We may have detected the Pele plume in reflected sunlight, at $0.27\mu m$, in July 1995, but did not see it 21 hours earlier, so the plume may be capable of rapid changes.

1. The Pele Plume

Pele was unique among the nine volcanic eruption plumes on Io discovered by Voyager [*Strom et al.*, 1981]. It was the highest plume (300 km), the most optically thin, and was the only one not active during both encounters. The Pele plume was not detected in Galileo images in June, September, or November 1996, but was seen in December 1996 [*McEwen et al.*, 1997a]. High-temperature thermal emission from Pele has been seen by Galileo's SSI [*Belton et al.*, 1996; *McEwen et al.*, 1997b], and NIMS [*Lopes-Gautier et al.*, 1997] instruments whenever observations have been made.

2. HST Observations

We imaged Io with the Wide-Field Planetary Camera 2 (WFPC2) on HST in July 1995 and July 1996 (Table 1). Image resolution was improved by Lucy-Richardson deconvolution.

A single F255W image taken on July 8 1995 shows a bright patch against dark sky off Io's limb in (Figure 1). The image is noisy, but the perfect alignment of the bright patch with the expected location of Pele, and the lack of similar features off Io's limb elsewhere in this and other F255W frames, gives us some confidence that this is the Pele plume. The plume is about 20 DN above background sky brightness, corresponding to an I/F value (the brightness ratioed to a normally-illuminated Lambert surface) of 0.004. This is similar to average $0.35\mu m$ Pele plume I/F values seen by Voyager 1 [*Strom et al.*, 1981, Figure 2]. No plume was seen in 0.373 μm images taken 20 minutes earlier.

An F255W image taken on July 7, when Pele should have appeared on the opposite limb, does not show the plume (Figure 1). Either the July 8 detection, or the July 7 non-detection, is spurious, or the plume switched on in the 21 hours between the frames. During the Voyager 1 encounter the Pele plume was active for at least 9 days, but these data suggest that more rapid variations are possible.

The Pele plume was definitely seen in three F255W images taken in Jupiter transit in July 1996 (Figure 1). The plume appears dark against Jupiter. Subsequent F336W and F410M images do not show the plume, though it was further from the limb when these images were taken (Table I). Partial saturation of Jupiter in the F336W image reduces the precision of measurements in this filter.

3. 1996 Plume Size and Density

To model the transit images, we ignore backscattered sunlight from the plume. This is justified if the plume activity level was similar on July 24 1996 and July 8 1995: the DN deficit in the plume in the July 1996 images, compared to the Jupiter background, is about 320 DN, compared to the 20 DN brightness of the July 1995 plume images. Also, modeling discussed below suggests that for dust or gas plume models that fit the transit observations, reflected sunlight is faint compared to absorbed or scattered Jupiter-light.

We modeled the plume as a uniform half-disk centered on the Pele vent (18 S, 256 W), including only that portion that would protrude above Io's limb. This model plume was smoothed by a 0.07 arcsec boxcar fil-

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[1] Lowell Observatory, Flagstaff, Arizona
[2] Institut d'Astrophysique de Paris, Paris
[3] Dept. of Atmospheric Oceanic, and Space Science, University of Michigan, Ann Arbor
[4] Lunar and Planetary Laboratory, University of Arizona, Tucson
[5] Space Telescope Science Institute, Baltimore, Maryland

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Table 1. Details of HST images

UT Date	UT Mid Time	HST Filter Name	Filter Wavelength Range, μm	Effective Wavelength, μm	Exposure (s)	Sub-Earth Lat.	Sub-Earth W. Long.	Solar Phase Angle	Δ (AU)	R (AU)	H (km)
95/07/07	14:01	F255W	0.257–0.291	0.272	600	-2.9	345.5	6.8	4.494	5.328	1.2
95/07/08	10:53	F255W	0.257–0.291	0.272	600	-2.9	162.4	7.0	4.503	5.328	2.8
96/07/24	19:12	F255W	0.257–0.291	0.272	600	-1.8	171.9	4.2	4.239	5.196	8.1
96/07/24	19:24	F255W	0.257–0.291	0.272	500	-1.8	173.7	4.2	4.239	5.196	13.9
96/07/24	20:45	F255W	0.257–0.291	0.272	500	-1.8	185.1	4.2	4.240	5.196	87.4
96/07/24	20:53	F336W	0.315–0.358	0.340	23	-1.8	186.2	4.2	4.240	5.196	97.8
96/07/24	20:59	F410M	0.400–0.417	0.409	10	-1.8	187.1	4.2	4.240	5.196	106.6

Comments: Filter wavelength range is between filter transmission half power points, after weighting by the solar spectrum. Effective wavelength is also weighted by the solar spectrum. H is the projected distance between the Pele plume source and Io's limb: this much of the bottom of the plume is hidden.

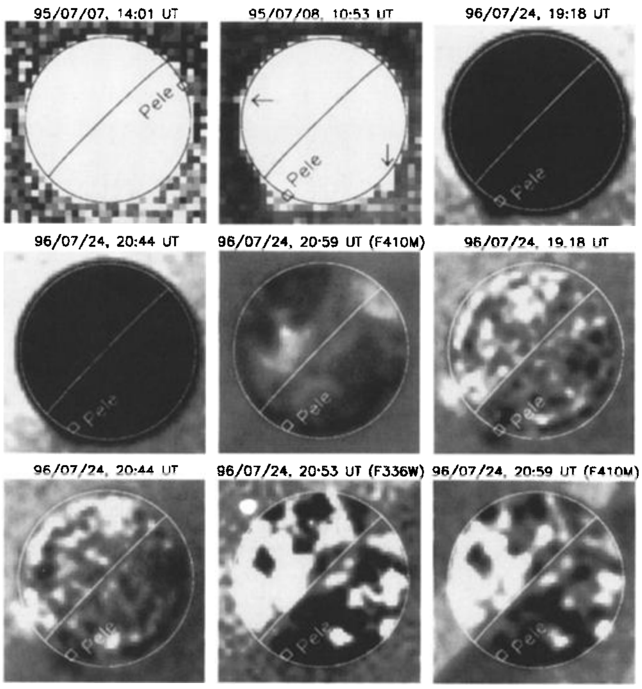

Figure 1. Detections, probable detections, and non-detections of the Pele plume in HST WFPC2 images. All are in the F255W filter except where noted. Io's limb, equator, and the expected location of the Pele source are shown in all frames. The plume is probably seen against dark sky on 95/07/08, at F255W: the arrows note imperfectly removed cosmic rays. However, it is not seen in 95/07/07 F255W images taken 21 hours earlier. The 1996 images have Jupiter in the background, and most are shown in both "raw" format and with plume visibility enhanced by ratioing each image to a transposed and registered copy of itself: the plume is then visible as both a positive image (dark spot off the limb) and negative image (bright spot off the limb). The Pele plume is seen in silhouette against Jupiter in the F255W images (the image labeled "19:18 UT" is an average of the 19:12 and 19:24 UT images), but not in the F336W or F410M images.

ter, and was then added to each HST image. Model size and brightness was adjusted to exactly remove the (negative) plume image. The model plume brightness was then translated into an optical depth by comparison with the brightness of the Jupiter background (Table 2).

Although the plume was further from the limb when the F410M image was taken, it should have been detected had it been as large and optically thick at this wavelength as in the F255W filter (Table 2). The plume height, 420± 40 km, makes this the largest plume ever seen on Io. December 1996 Galileo images show a Pele plume of similar height [*McEwen et al.,* 1997a].

4. Models: Dust Scattering

Voyager 1 observations of the Pele plume at wavelengths $\geq 0.35\mu$m, show a neutral color. However, the Voyager 1 outer Loki plume was blue in the 0.35-0.6μm wavelength range, while the inner Loki plume was red [*Collins,* 1981]. Collins attributed the blue color of the outer Loki plume to scattering by particles much smaller than the wavelength of light, and this may also explain the HST color of the Pele plume.

Table 2. Plume optical depths, July 1996

Filter	Sub-Earth W. Long.	H, km	Pele Plume Optical Depth	Pele Plume Radius km
F255W	172.8[a]	11.0	0.19±0.05	420±40
F255W	185.1	87.4	0.17±0.07	440±80
F336W	186.2	97.8	$\leq$0.15	–
F410M	187.1	106.6	$\leq$0.06	–

Comments: H is defined as in Table 1

[a] Average of first two 97/07/24 frames.

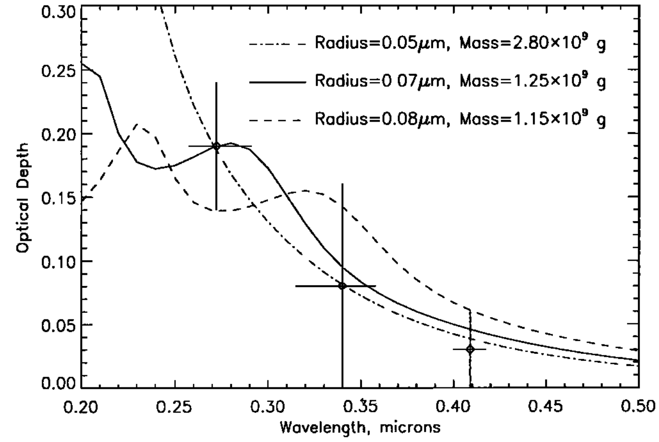

Figure 2. Observations of the July 1996 Pele plume optical depth, compared to dust scattering models described in the text. The oscillations in the Mie curves are due to our assumption of a single particle size in each model. Horizontal bars show the wavelength range of each filter (Table II), and vertical error bars show the uncertaintly in the observed optical depth. The two longer wavelength observations are upper limits. Particle radii $\leq 0.08\mu$m are required to match the observations.

We modeled the plume as a 420 km radius cloud of spherical particles with uniform projected optical depth, using Mie theory [*Bohren and Huffman,* 1983, Appendix A], and assuming the sulfur real refractive index of 1.957. For relevant particle sizes, the value of the complex refractive index is unimportant. We determined the amount of direct Jupiter light scattered out of the beam, the amount of Jupiter light scattered into the beam from other parts of the planet (which was negligible), and the amount of light added to the plume image by backscattered sunlight.

The HST plume color requires particles with radius $r \leq 0.08\mu$m (Figure 2). The plume mass m needed to match the F255W optical depth increases with decreasing particle size, because smaller particles are much less efficient scatterers. For $r = 0.07\mu$m, $m = 1.25\pm0.3\times10^9$ g. Particles with $r = 0.05 - 0.08\mu$m are poor backscatterers, and the backscattered sunlight added to the plume is only 10–20% of the scattered Jupiter light lost from it in the F255W filter, consistent with the plume's dark appearance and justifying our neglect of backscattered sunlight in deriving optical depths. Particles smaller than 0.02 μm scatter too isotropically to be consistent with the observed darkness of the plume.

Application of the Mie scattering model to the tentative July 8 1995 observation of Pele in backscattered sunlight, assuming the same plume radius as the 1996 observations, gives $m = 6\times10^8$ g for $r = 0.07\mu$m, about half the July 1996 mass.

Collins [1981] used a Rayleigh-like particle scattering law, valid only for $r \leq 0.01\mu$m, to model the Voyager images of the Loki plume. He derived $m \geq 10^{11}$ g for the outer part of the plume, for $r \leq 0.01\mu$m. Our Mie scattering code, approximating the Loki plume as a uniform hemisphere with a 0.34μm I/F of 0.03 and radius of 200 km, gives a plume mass of 9.3×10^{10} g for $r = 0.01\mu$m, confirming Collins' result. However, the Mie code can also match the color and brightness of the outer Loki plume with $r = 0.05\mu$m and $m = 1.1\times10^9$ g, comparable to our minimum dust mass for Pele. The Loki plume may therefore be much less massive than deduced by Collins, if r is larger than he assumed.

5. Models: SO_2 Gas Absorption

The extinction of Jupiter light by the Pele plume in the F255W filter image may also be explained by the presence of SO_2 gas, which would make Pele a "stealth plume" [*Johnson et al.,* 1995]. SO_2 gas absorption [*Mannatt and Lane,* 1993] is much more efficient in the F255W filter than at longer wavelengths. The SO_2 absorption cross-section σ in the F255W filter bandpass, weighted by the spectrum of reflected light from Jupiter (Mark Vincent, pers. comm.), is $\approx 5\times10^{-19}$ cm^2. Assuming SO_2 absorption is in the linear regime [*Ballester et al.,* 1994], the observed optical depth of 0.19 gives a column abundance $N \approx 3.7\times10^{17}$ cm^{-2}. This value is approximate, because the Manatt and Lane SO_2 spectrum is at 300 K, and has relatively low spectral resolution. This amount of gas would not produce detectable absorption in the F336W and F410M filters.

Our inferred SO_2 abundance is comparable to other estimates of local SO_2 abundance on Io. The darkness of Io's disk near Pele in 0.2–0.3μm HST images suggested $N = 10^{18}$ cm^{-2} [*Sartoretti et al.,* 1996], dependent on assumptions about the surface albedo. Voyager infrared spectra gave $N = 5\times10^{18}$ cm^{-2} over Loki [*Pearl et al.,* 1979]. HST spectroscopy detected SO_2 absorption localized above Pele in early August 1996, shortly after our Jupiter transit observations (McGrath et al., pers. comm.), supporting the SO_2 model for our observations but not ruling out the presence of dust in addition.

The total mass of gas over Pele derived from our 1996 observations, if the exinction is due to SO_2, is 1.1×10^{11} g, about 100 times the minimum mass of dust required to explain the same observations. Rayleigh scattering is negiligible for these gas abundances [*Collins,* 1981], as is refraction.

6. Resurfacing Rates

Using a ballistic approximation, a 420 km plume altitude requires a launch speed of 1.1 km/s (43% of Io's escape velocity, but physically plausible [*Keiffer,* 1982]), and a flight time of 1630 sec, including the reduction in gravity with altitude. With a plume dust mass of 10^9 g, a 420 km radius fallout area, and a particle density of 1 g/cm^3, this gives a minimum resurfacing rate of 3.5×10^{-3} cm/yr, equivalent to a global rate of 4.6×10^{-5}

cm/yr. *Johnson et al.* [1979] estimated a global plume resurfacing rate of 3.5×10^{-4} cm/yr). The much larger global plume resurfacing rates of $\sim 10^{-2} - 1$ cm/yr estimated by [*Johnson and Soderblom,* 1982] resulted from the high Loki plume mass determined by [*Collins,* 1981], and may thus be too large.

Our minimum July 1996 Pele dust resurfacing rate gives only 10 microns of deposition in the four months between Voyager 1 and Voyager 2, probably insufficient to produce the major albedo changes seen at Pele in that interval. Either the plume is much more massive than our lower limit, due to a large population of particles larger or smaller than 0.07μm, or to a large gas content, or it was much more massive during the Voyager era.

If the observed plume is due to SO_2 gas, simple scaling from the dust calculation gives a large local SO_2 deposition rate of 0.39 cm/yr. The Pele ejecta deposits, however, appear to be poor in SO_2 frost [*McEwen et al.,* 1988]. If the plume we see is due to SO_2, the ultimate fate of that SO_2 is an interesting question: perhaps it flows horizontally to high-albedo cold traps elsewhere [*Ingersoll,* 1989].

7. Conclusions

These observations show that the largest of Io's plumes can be detected from Earth, opening up a new avenue for study of these remarkable phenomena. The 1996 transit observations may be due to dust or gas, but the tentative 1995 observations of the plume in backscattered sunlight would require a dust component. If the plume is due to gas, the F255W Jupiter transit images in Figure 1 provide dramatic visual confirmation of the patchy-atmosphere model derived from theoretical and observational considerations [*Ingersoll,* 1989; *Lellouch et al,* 1992; *Ballester et al.,* 1994; *Sartoretti et al.,* 1996], by directly imaging a large, volcanically-derived atmospheric "patch" over Pele. If the 1995 observations in backscattered sunlight are real, they provide evidence for very rapid time variations in the Pele plume.

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References

Belton, M. J. S. and the Galileo SSI team, Galileo's first images of Jupiter and the Galilean satellites, *Science, 274,* 377-385, 1996.

Ballester, G. E., McGrath M. A., Strobel D. F., Zhu X., Feldman P. D., and Moos H. W., Detection of the SO2 atmosphere of Io with the Hubble Space Telescope, *Icarus, 111,* 2-17, 1994.

Bohren, C. F., and D. R. Huffman, *Absorption and scattering of light by small particles,* Wiley, New York, 1983.

Collins, S. A., Spatial color variations in the volcanic plume at Loki, on Io, *J. Geophys. Res. 86,* 8621-8626, 1981.

Ingersoll, A. P., Io meteorology: How atmospheric pressure is controlled locally by volcanoes and surface frost, *Icarus 81,* 298-313, 1989.

Johnson, T. V., A. F. Cook, C. Sagan, and L. A. Soderblom, Volcanic resurfacing rates and implications for volatiles on Io. *Nature 280,* 746-750, 1979.

Johnson T. V., and L. A. Soderblom, Volcanic eruptions on Io: Implications for surface evolution and mass loss. in *Satellites of Jupiter* edited by D. Morrison, pp. 634-646, U. Arizona Press, Tucson, 1982.

Johnson T. V., D. L. Matson, D. L. Blaney, G. J. Veeder, and A. G. Davies, Stealth plumes on Io, *Geophys. Res. Lett. 22,* 23, 1995.

Keiffer S. W., Dynamics and thermodynamics of volcanic eruptions: implications for the plumes of Io. In *Satellites of Jupiter,* edited by D. Morrison, pp. 647-723, U. Arizona Press, Tucson, 1982,

Lellouch, E., M. J. S. Belton, I. DePater, G. Paubert, S. Gulkis, and T. Encrenaz, The structure, stability, and global distribution of Io's atmosphere, *Icarus 98,* 271-95, 1992.

R. Lopes-Gautier, A. G. Davies, R. Carlson, W. Smythe, L. Camp, L. Soderblom, F.E. Leader, R. Mehlman, and the Galileo NIMS team, Hot spots on Io: Initial results from Galileo's Near Infrared Mapping Spectrometer, *Geophys. Res. Lett.,* this issue, 1997.

Manatt, S. L. and A. L. Lane, A compilation of SO_2 absorption cross-sections from 106-403 nm, *J. Quant. Spectrosc. Radiat. Trans. 50,* 267-276, 1993.

McEwen A. S., T. V. Johnson, D. L. Matson, and L. A. Soderblom, The global distribution, abundance, and stability of SO_2 on Io, *Icarus 75,* 450-478 1988.

McEwen, A. S., J. Spencer, D. Simonelli, T. Johnson, L. Keszthelyi, and the Galileo SSI Team, Io plume observations from Galileo and HST, *Lunar Planet. Sci. XXVIII,* 911, 1997a.

McEwen, A. S., D. P. Simonelli, D. Senske, K. P. Klaasen, L. P. Keszthelyi, T. V. Johnson, P. Geissler, M. H. Carr, and M. J. S. Belton, High-temperature hot spots on Io as seen by the Galileo Solid State Imaging (SSI) experiment. *Geophys. Res. Lett.,* this issue, 1997b.

Pearl, J. C., R. Hanel, V. Kunde, W. Maguire, K. Fox, S. Gupta, C. Ponnamperuma, and F. Raulin, Identification of gaseous SO_2 and new upper limits for other gases, *Nature 280,* 757-758, 1979.

Sartoretti, P., M. J. S. Belton, and M. A. McGrath, SO_2 distributions on Io, *Icarus 122,* 273-287, 1996.

Strom RG, Schneider NM, Terrile RJ, Cook AF, and Hansen C., Volcanic eruptions on Io, *J. Geophys. Res. 86,* 8593-8620, 1981.

J. R. Spencer, Lowell Observatory, 1400 W. Mars Hill Rd., Flagstaff AZ 86001. (e-mail: spencer@lowell.edu)

P. Sartoretti, Institut d'Astrophysique de Paris, 98 bis Boulevard Arago, 75015 Paris, France.

G. E. Ballester, J. T. Clarke, Dept. of Atmospheric Oceanic, and Space Science, University of Michigan, 2455 Hayward, Ann Arbor, MI 48109.

A. S. McEwen, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.

M. McGrath, Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218.

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