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AN IO-EARTH COMPARISON OF VOLCANIC ACTIVITY IN THE WAKE OF GALILEO AND CASSINI

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Io provides an opportunity to study volcanic processes on scales and at temperatures never witnessed on Earth, but which may have shaped the planet billions of years ago [1]. Study of Galileo data obtained by the Solid State Imaging (SSI) experiment and the Near-Infrared Mapping Spectrometer (NIMS), and Cassini imaging experiment (ISS) has allowed the style of eruption at different volcanoes to be identified and the evolution of individual eruptions to be charted [2]. These can be compared to their terrestrial counterparts. For example, the "thermal signature" at Pele is indicative of a long-lived active lava lake, which exhibits a thermal flux per unit area comparable with the Kupaianaha, Hawai'i, lava lake during its most active stage [2]. Cassini observations show variations at short timescales [3]. The Pillan 1997 eruption emplaced large sheet flows, and exhibited thermal fluxes similar to terrestrial flows at Krafla and Etna [4]. Additionally, the relatively low (compared with Pillan and Pele) but steady thermal output from the compound flows at Prometheus and Amirani (implied by model fits to NIMS G1 data [5] and imaged by SSI [6] and NIMS [7] during close encounters) show thermal emission fluxes similar to equivalent emplacement styles on Earth, such as Hawaiian compound flow fields [8]. It is possible to estimate volumetric eruption rate (an important eruption parameter) for a number of volcanoes from NIMS data [2,8,9]. These analyses show that, as a function of emplacement style, volumetric eruption rates on Io are greater than their terrestrial counterparts while still exhibiting similar mass and thermal fluxes per unit area [2,8]. However, there does not appear to be a terrestrial equivalent to Loki. Periodic brightenings [10] indicate widespread and intense volcanic activity, and the periodicity, coupled with observed surface-age distributions [11], might be indicative of Loki being an overturning lava lake, rather than being resurfaced by flows. If so, then this is a lava lake on a spatial scale orders of magnitude greater than that seen on Earth. The thermal signature of activity at Loki is similar to that of "Promethean" volcanoes, exhibiting a steady thermal ramp towards longer NIMS wavelengths (0.7 to 5.3 microns), but on a much larger areal scale. Unlike Pele and Pillan in 1997 (but like Prometheus) Loki does not exhibit much short-wavelength (e.g. 1 micron) emission compared to that emitted at longer-wavelengths (e.g. 5 micron), even at its most active as seen by NIMS [12]. This indicates that despite being the most powerful thermal source on Io, the volcanic activity at Loki is relatively gentle or includes cooler lavas than those seen at Pele and Pillan. To summarise, remote observations of Io's volcanism compare well with those of terrestrial volcanism, providing a synergistic analysis of data from both bodies. Testing of lava emplacement and cooling models with terrestrial data increases confidence in modelling these processes on Io [e.g., 13]. This work was carried out at the Jet Propulsion Laboratory-California Institute of Technology, under contract to NASA. AGD is supported by NASA JSDAP and PG&G grants. References: [1] Matson et al., 1998, LPSC 29 abstract. [2] Davies et al., 2001, JGR, 106, 33,079-33,103. [3] Radebaugh et al., 2002, LPSC 33 abstract. [4] Keszthelyi et al., 2001, LPSC 32 abstract. [5] Davies et al., 2000, Icarus, 148, 211-225. [6] Keszthelyi et al., 2001, JGR, 33,025-33,052. [7] Lopes et al., 2001, JGR, 106, 33,053-33,078. [8] Davies, 2001, LPSC 32 abstract. [9] Davies, 1996, Icarus, 124, 45-61. [10] Rathbun et al., 2001, LPSC 32 abstract. [11] Lopes et al., 2002, LPSC 33 abstract. [12] Davies et al., 2000, LPSC 31 abstract. [13] Davies et al., EOS, 81, no. 19, p S291.

An Io-Earth Comparison of Volcanic Activity in the Wake of Galileo and Cassini

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Introduction

- Monitoring remote terrestrial volcanoes from orbiting platforms has now become routine.
- Io provides an opportunity to compare terrestrial volcanism with extraterrestrial volcanism.
- GLL NIMS and SSI data, augmented with CAS ISS data, have provided the ability to classify styles of eruption on Io, which can be compared with terrestrial equivalents.

Galileo observes volcanism on Io

- SSI can detect the hottest areas of active volcanism, in excess of 700 K
- NIMS is good at detecting cooler areas
  - Many nightside spectra of volcanoes
  - 0.7-5.2 microns coverage range is ideal, with sensitivity down to ~200 K
  - Good spectral resolution (mostly)
  - Low spatial resolutions prior to I24 are not a problem as we want the *total* thermal output
- PPR provides longer wavelength constraints
- Joint NIMS-SSI datasets provide the best constraints on magma temperature

Cassini observes volcanism on Io

- ISS, like SSI, can detect the hottest areas of active volcanism, in excess of 700 K
- VIMS, like NIMS, is good at detecting cooler areas
- Cassini obtained very high temporal resolution data from the GLL-CAS G29 Millennium flyby (Dec 2000) (Radebaugh et al., 2001 DPS; Radebaugh et al.; 2002, LPSC)
- Joint NIMS-SSI datasets provide the best constraints on magma temperature and areas of emitting surfaces

Terrestrial remote observations of volcanism

- Most useful data to date comes from weather satellites (similar time scales of order of hours).
- NOAA GOES and AVHRR satellites are especially useful.
- GOES: geostationary: 4 km/pixel, 4 bands from 0.5-12 microns.
- AVHRR: polar orbiters: >1km pixel. 5 bands from 0.5-12 microns.
- GOES data have been used to determine the timing of events during an eruption.
- AVHRR data have been used to identify the types of active volcanic features at several volcanoes.

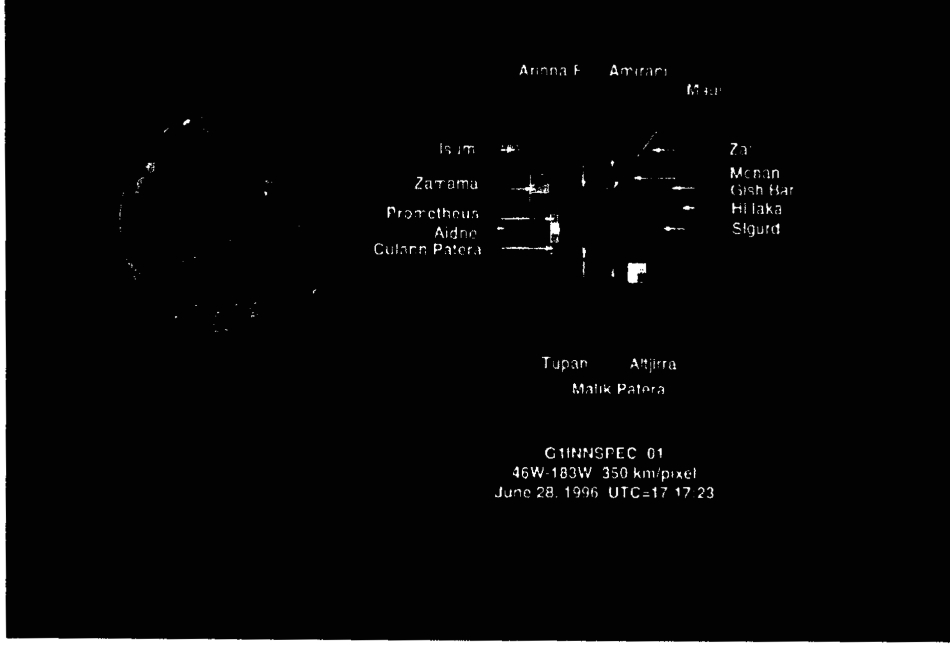
Terrestrial remote observations of volcanism, cont'd.

- Now we have Terra data providing high-spectral resolution data on (typically) a month-to-month temporal scale.
- 200 km altitude, highly-inclined orbit
- ASTER
    - SWIR
    - MISR
    - TIR

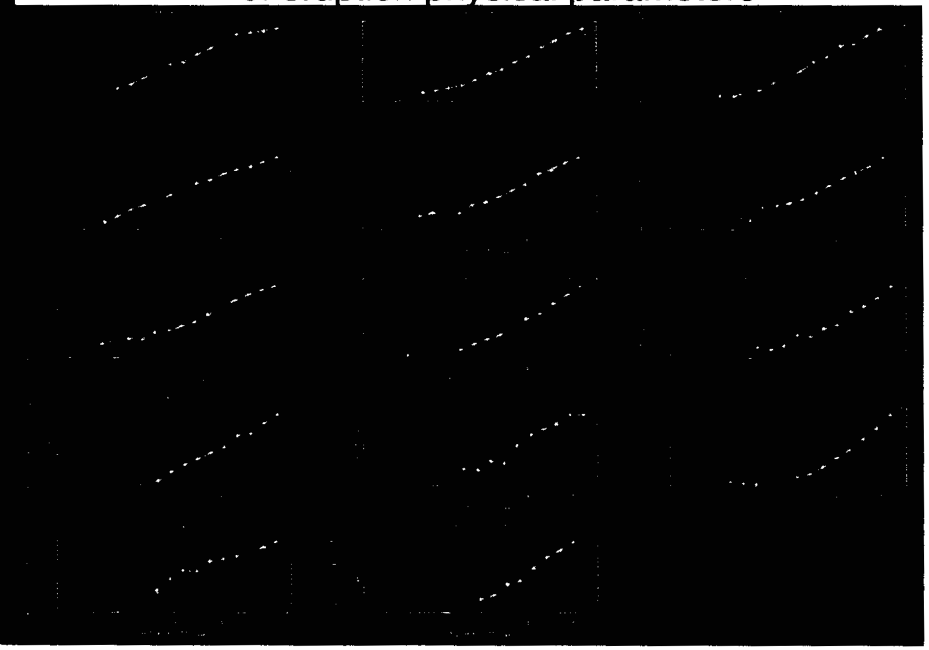
Fun things you can do with NIMS data

- Chart thermal evolution of individual eruptions
- Derive eruption style from temporal evolution of thermal signature
- Determine minimum lava eruption temperature (best done with combined NIMS-SSI data)
- Determine rates of areal coverage
- Determine mass eruption rates
- Estimate flow thicknesses (this allows more detailed flow modelling)

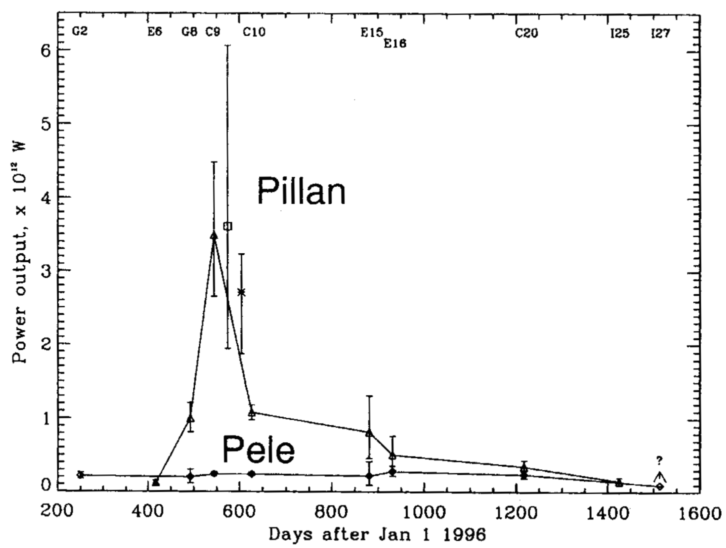
Thermal Map and Cooling Model Fits



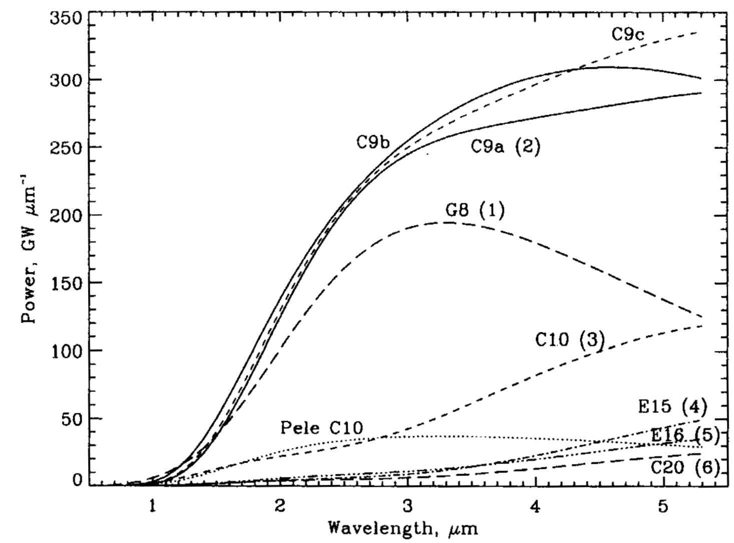
Thermal emission model fits and derivation of eruption physical parameters



Temporal evolution of total output



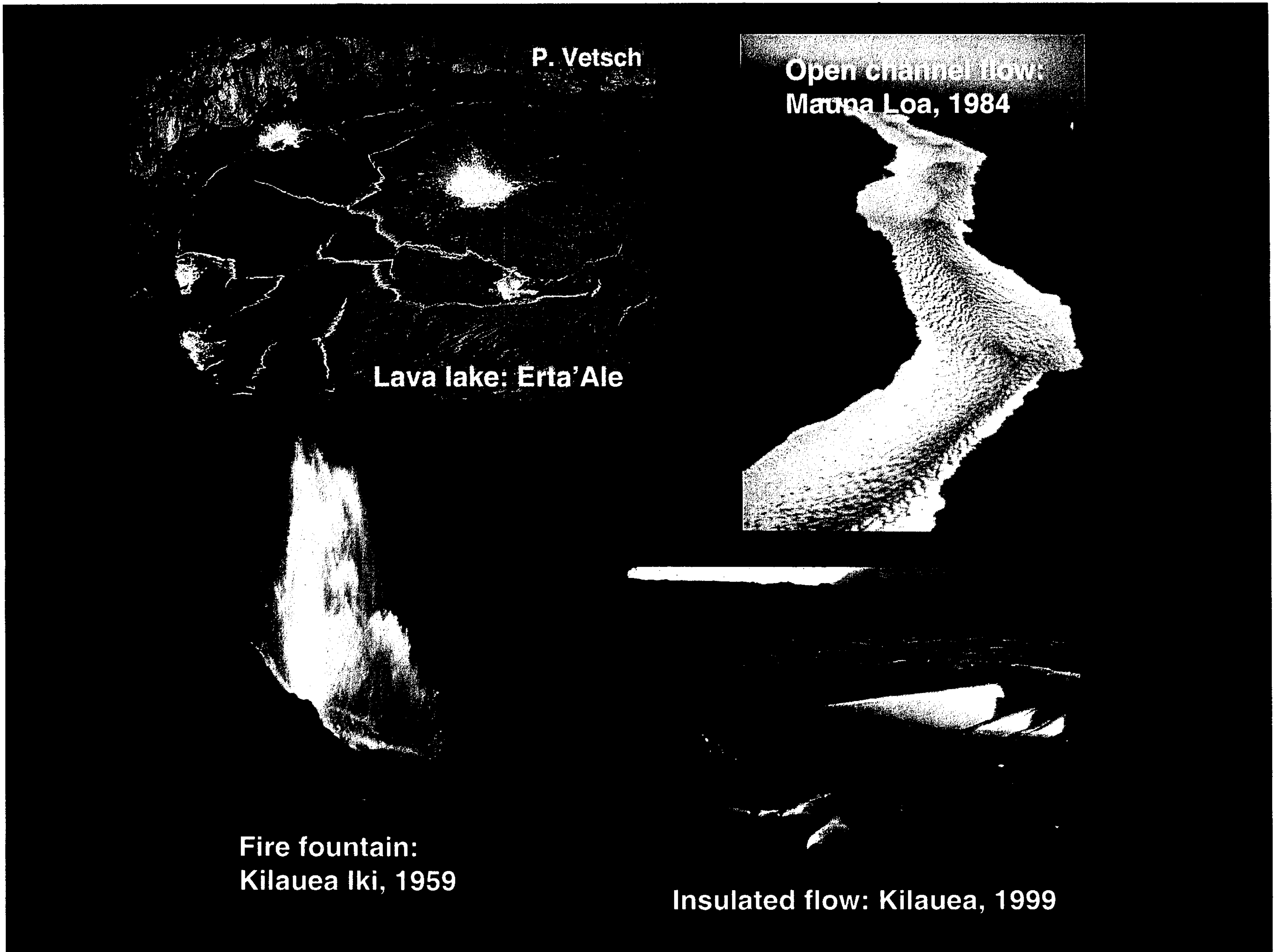
Eruption signature evolution



Criteria for interpreting Thermal Emissions from Active Volcanism on Io and the Earth

Style of volcanic activity	*Characteristics*
Lava lake	Long-lived, small, geographically fixed hot spot with high/medium average surface temperatures and minimal temporal variations
Lava fountain	Short lived, medium size, fixed hot spot with high average surface temperatures and rapid decay in intensity
Open channel or sheet flow	Short lived, large hot spot that grows in size with medium to high average surface temperature that gradually decays
Insulated (tube fed) flow field	Long lived, wandering hot spot with low average surface temperature

Keszthelyi *et al.*, 2001, LPSC-32 abstract 1523


P. Vetsch
Lava lake: Erta'Ale
Open channel flow:
Mauna Loa, 1984
Fire fountain:
Kilauea Iki, 1959
Insulated flow: Kilauea, 1999

Thermal Characteristics of some Ionian Volcanoes

Centre	Eruptive Style	Thermal Characteristics
Pele	Lava lake	Steady, fixed emission of 210-280 GW (~15 kW/m^2)
Pillan	Open channel flow	Dropped from 3600 GW to 350 GW as hot area decreased from 30 km^2 to 0.5 km^2.
Prometheus	Insulated flow field	Steady emission of ~100 GW (~2 kW/m^2), moved ~80 km in ~20 years.
Amirani	Insulated flow field	Steady emission of ~300 GW (~2 kW/m^2), multiple centers of activity, some shifted ~100 km.

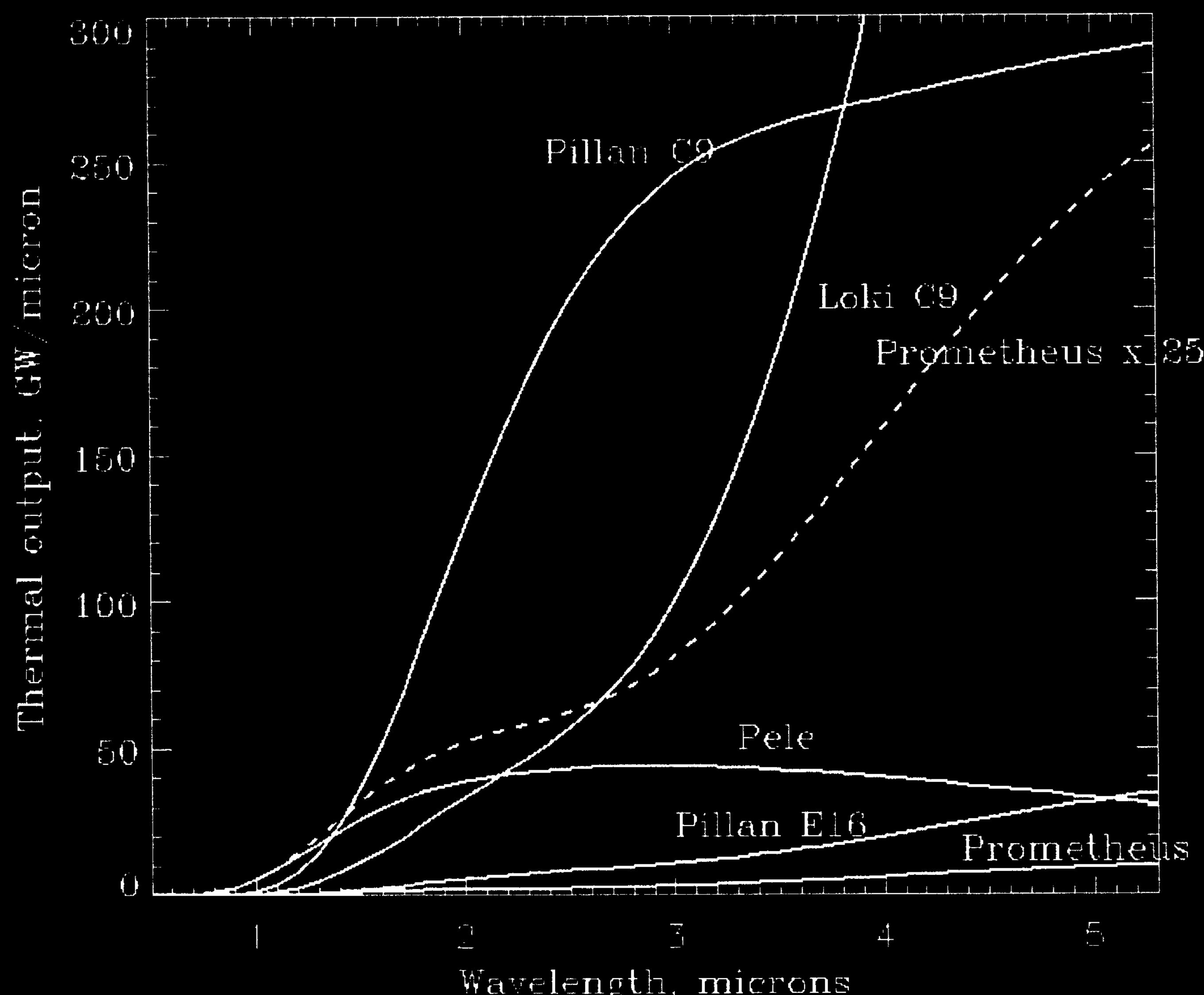
Keszthelyi *et al.*, 2001, LPSC-32 abstract 1523

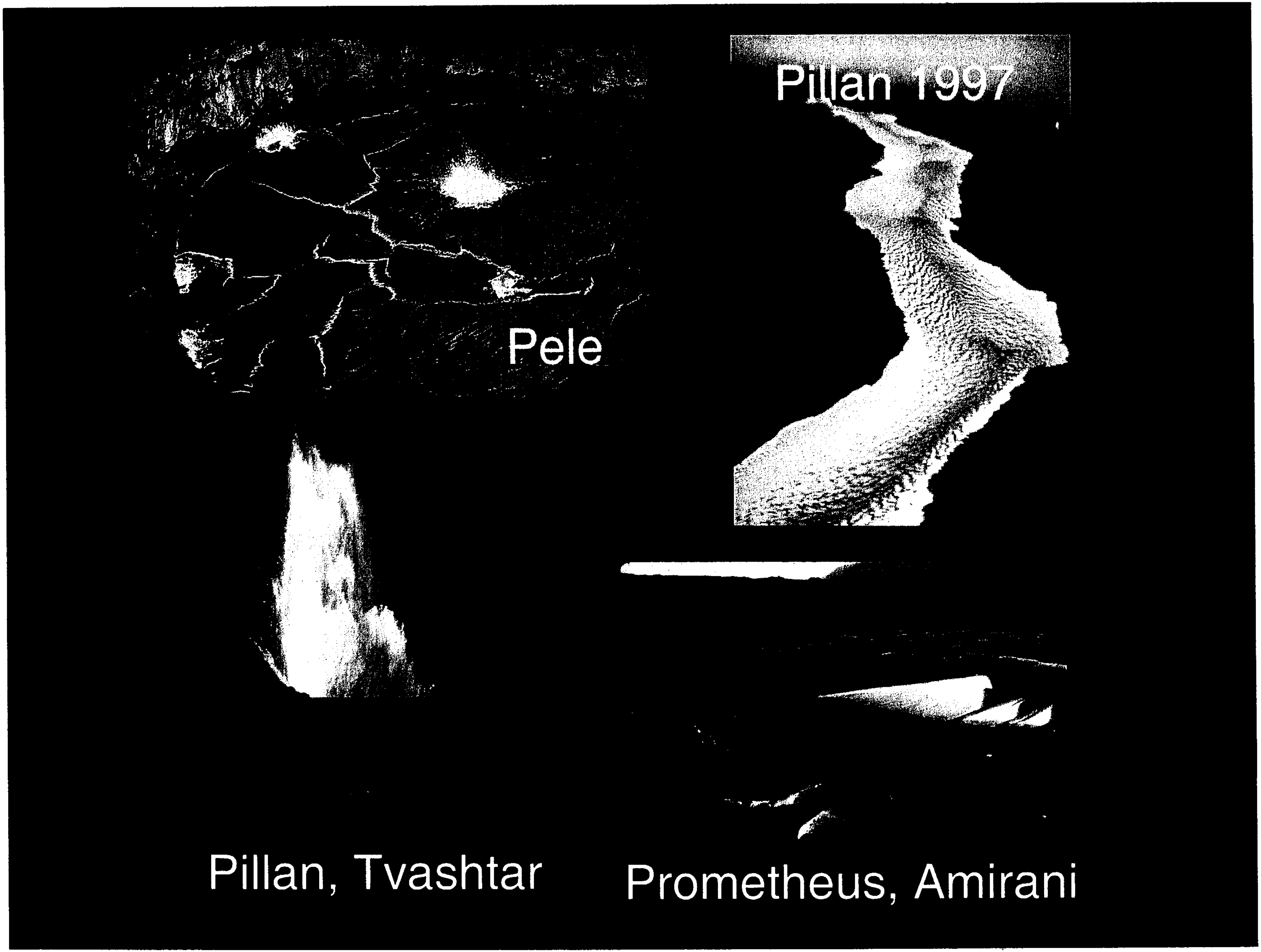
Thermal Characteristics of some Terrestrial Volcanoes

Volcano	Eruptive Style	Thermal Characteristics
Erebus	Lava lake	Steady, fixed emission of 0.05-0.1 GW (1-6 kW/m^2)
1992 Etna	Open channel and tube-fed a-a flows	Peak at 7.3 GW, drop to 0.5 GW (1.2-3.5 kW/m^2), while the hot area varied between 3.7 km^2 and 0.1 km^2.
1991 Kilauea	Tube-fed pahoehoe	0.3-0.7 GW (0.1-0.05 kW/m^2),
1984 Krafla	Lava fountain and open sheet flows	26-50 GW (~0.5-1.5 kW/m^2),

Keszthelyi *et al.*, 2001, LPSC-32 abstract 1523

Io: thermal emission spectra as function of eruption style




Pillan 1997
Pele
Pillan, Tvashtar
Prometheus, Amirani

Lava lake flux and mass densities: Io and Earth

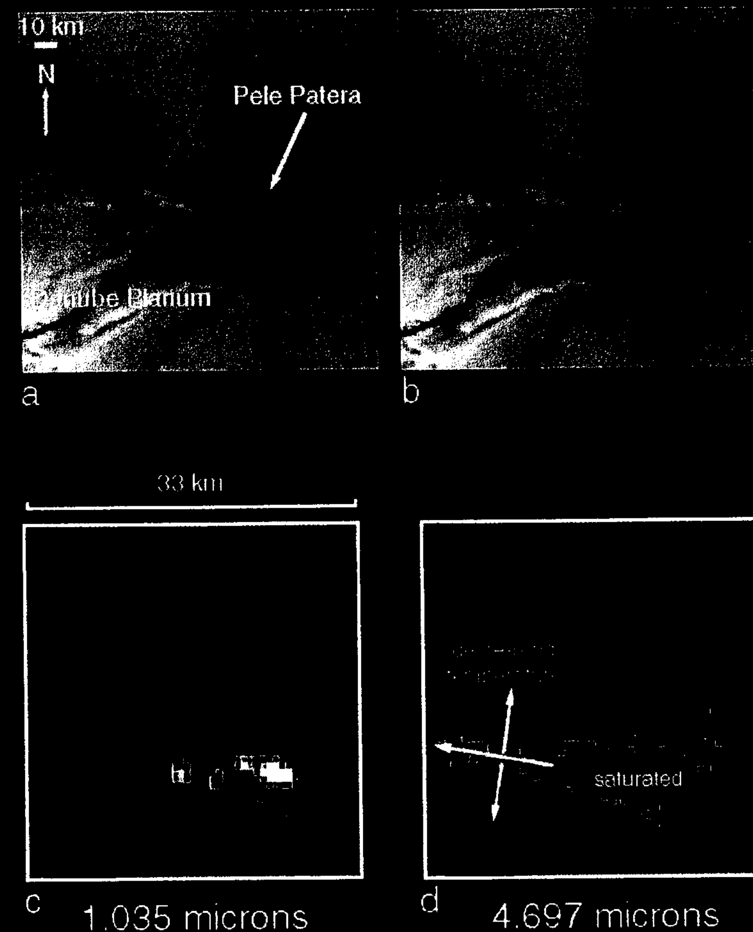
Lake	Date	Total flux, Q_{tot} GW	Mass flux (a), M Kg s^{-1}	Flux density (Q_{tot} m^{-2}) kW m^{-2}	M/m^2 kg s^{-1} m^{-2}
Erebus	January 1985	0.016-0.103	38-76	89-572	0.2-0.4
Pu'u O'o	July 1991	0.508-0.674	1553-2079	128-170	0.4-0.5
Nyiragongo	1972	5.150	8162-10350	114	0.2
Erebus	January 1989	0.013-0.108	30-69	43-359	0.1-0.2
Erta 'Ale	January 1973	4.728	14902-18204	50	0.2
Kupaianaha Stage 1	**Oct 87/Jan 88**	**0.018**	**41-57**	**~22**	**0.018-0.025**
Pele, E16, NIMS	**20 July 1998**	**280**	**644,000-889,000**	**17**	**0.04-0.05**
Nyiragongo	August 1987	0.0002-0.0006	1-2	15-20	0.03-0.1
Erta 'Ale	January 1986	0.018-0.031	44-104	6-11	0.02-0.04
Pele, IRIS	1979	1160	2.67×10^6-3.68×10^6	10	0.02-0.03
Pele, IRIS	1979	1333	3.07×10^6-4.23×10^6	6	0.01-0.02
Kupainaha Stage 2	Oct 87/Jan 88	0.014	32-44	5.3	0.014-0.019
Kupainaha Stage 3	Oct 87/Jan 88	0.011	25-35	4.9	0.011-0.015
Loki	1979	12600	2.9×10^7-$4. \times 10^7$	0.3	0.00007-0.0001

Davies *et al.*, 2001

Lava lakes on Earth and Io

Kupaianaha, Hawai'i, 1986

Pele, Io, 2000 (I27)



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Davies *et al.*, 2001

E comparisons: Io and Earth

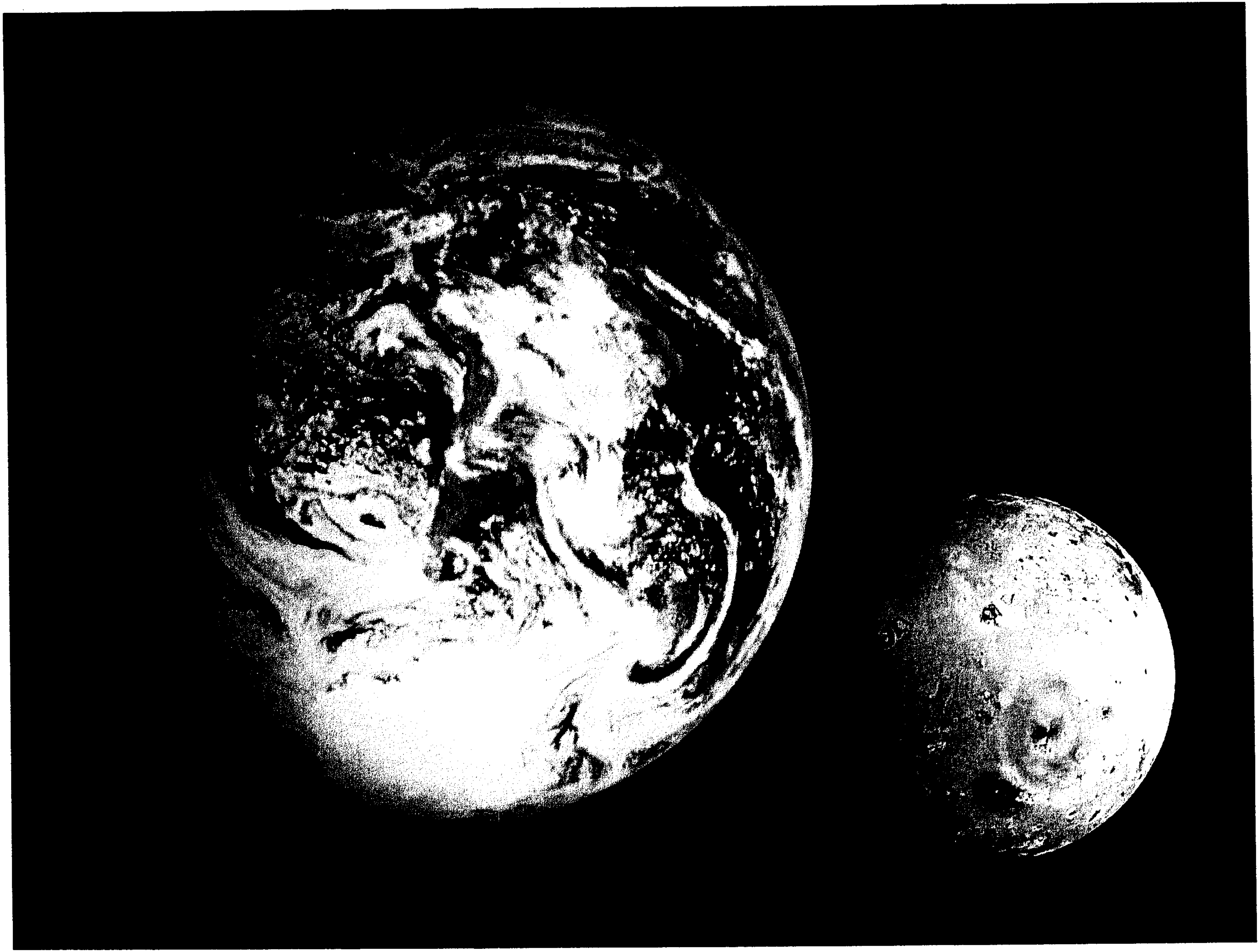
Io

- Outburst (Loki?) — **10^5 to 10^6 m^3/s** (Blaney *et al.*, 1995; Davies, 1996)
- Pillan 1997 — **10^3 to 10^4 m^3/s** (Davies *et al.*, Williams *et al.*, 2001)
- Pele — **~250 to 350 m^3/s** (Davies *et al.*, 2001)
- Amirani+Maui — **55 to 100 m^3/s** (Keszthelyi et al., 2001; Davies, 2001)
- Prometheus — **>5 to 35 m^3/s** (McEwen *et al.*, 2000; Davies *et al.*, 2001)
- G1 volcanoes (average) — **16 m^3/s** (ultramafic) to **27 m^3/s** (basalt)
  33 m^3/s using IFM (Davies et al., 2000)

Earth

- Laki, Iceland — **8700 m^3/s** (Thordarsson and Self, 1993)
- Mauna Loa, Hawai'i — **10 to 1000 m^3/s** (Malin, 1980)
- Kilauea Iki, Hawai'i — **100 m^3/s** (Malin, 1980)
- Kupaianaha, Hawai'i — **~50 m^3/s** (stage 1) (Flynn *et al.*, 1993)
- Kilauea, Hawai'i — typically **~2 m^3/s** (Malin, 1980)

Davies, 2001.



Conclusions: similarities

- Thermal signatures of eruption styles are similar on Earth and Io, despite different eruption environments.

- Ionian eruptions are very similar to terrestrial eruptions of the *same style* (e.g., Pele and Kupaianaha, Prometheus and Kilauea, etc.)

- Although Ionian volcanoes are more extensive areally, mass and thermal fluxes are similar for similar eruption styles. This suggests that the techniques we have developed for both Earth and Io are robust and trustworthy.

- In short, any given area of an ionian eruption looks very much like its terrestrial counterpart

Conclusions: differences

- Io NIMS data have better *spectral* resolution that any terrestrial data, without pesky atmospheric absorptions. Terrestrial platforms have better *temporal* resolution.
- Io eruptions are monitored on temporal scales of weeks to months from Galileo: happily, Cassini has obtained observations on scales of minutes for two hours, better than the 15 min time scale obtained by GOES.
- Ionian volcanoes and eruptions are larger areally. (See Davies, 2001, and 2001 JGR Io Special Issue papers: Keszthelyi *et al.*, 2001 LPSC abstract).
- Io activity is generally more voluminous and may involve hotter magmas: these combine to generate larger thermal fluxes.

Acknowledgements

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