great as modern recharge [M. S. Bedinger *et al.*, *U.S. Geol. Surv. Open File Rep. 84-738* (1984)]. We consider that the Ash Meadows system is approximately a constant volume system with residence times inversely proportional to recharge rates. Second, during pluvial and stadial climates significant recharge likely also occurred on the numerous ridges of intermediate altitude (<1800 m) (Fig. 1). These ridges, which are outcrops of the regional aquifer, are all much closer to the Ash Meadows oasis than the Spring Mountains and Sheep Range; hence, recharge from these ridges would have a much shorter travel time to Devils Hole.

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The most comprehensive recent attempt at direct dating of a deep-sea core is that of Kominz *et al.* [M. A. Kominz, G. R. Heath, T.-L. Ku, N. G. Pisias, *Earth Planet. Sci. Lett.* **45**, 394 (1979)]. They dated Pacific core V28-238 with ^{230}Th-^{234}U and obtained an age of 145 ± 9.5 ka for termination II and 260 ± 30 ka for termination III. Kominz *et al.* explicitly noted the major discrepancy between their ^{230}Th date and the widely accepted age of 127 ka for termination II.

Searles Lake, just 140 km southwest of Devils Hole, has a paleoclimatic record that extends for 3 million years [J. L. Bischoff, R. J. Rosenbauer, G. I. Smith, *Science* **227**, 1222 (1985); G. I. Smith, V. I. Barczak, G. F. Moulton, J. F. Liddicoat, *U.S. Geol. Surv. Prof. Pap. 1256* (1983)]. The 6/5 isotopic boundary (termination II) of the marine $\delta^{18}O$ record coincides with a major deepening, rather than the expected shallowing of this lake, whereas the 2/1 boundary (termination I) coincides with desiccation of Searles Lake, as expected. Thus, this continental record also does not mimic the marine record. The DH 2 $\delta^{18}O$ record (Figs. 3 and 4) clearly indicates that a major stadial had begun by 127 ka.

In high-latitude caves, periods of speleothem deposition and nondeposition are believed to indicate respectively interglacial and glacial climates. U-series dated speleothems from such caves located in areas overridden by or adjacent to an ice sheet suggest that the last interglacial stage began between 170 and 135 ka [M. Gascoyne, *Stud. Speleol.* **V**, 15 (1984); R. S. Harmon, D. C. Ford, H. P. Schwarcz, *Can. J. Earth Sci.* **14**, 2543 (1977); R. S. Lively, *Geology* **11**, 259 (1983); R. S. Harmon, *Natl. Speleol. Soc. Bull.* **41**, 102 (1979); M. Gascoyne, H. P. Schwarcz, D. C. Ford, *Phil. Trans. R. Soc. Lond. Ser. B* **301**, 143 (1983)].

In summary, there is abundant proxy marine and continental evidence, all ^{230}Th-^{234}U dated, that the transition to interglacial climates occurred sometime between 135 and 170 ka. No one of these proxy records would, by itself, constitute a challenge to the widely accepted 130 ka age for termination II. When considered together, however, they provide strong independent support for the pre-147-ka age for termination II indicated by DH 2.

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Io: Evidence for Silicate Volcanism in 1986

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Infrared observations of Io during the 1986 apparition of Jupiter indicate that a large eruptive event occurred on the leading side of Io on 7 August 1986, Universal Time. Measurements made at 4.8, 8.7, and 20 micrometers suggest that the source of the event was about 15 kilometers in radius with a model temperature of ~900 Kelvin. Together with previously reported events, these measurements indicate that high-temperature volcanic activity on the leading side of Io may be more frequent than previously thought. The inferred temperature is significantly above the boiling point of sulfur in a vacuum (715 Kelvin) and thus constitutes strong evidence for active silicate volcanism on the surface of Io.

Since the discovery of volcanic activity on Jupiter's satellite Io (*1*), the nature of the thermal activity has been studied through a combination of analyses of Voyager data and Earth-based infrared telescopic observations. The range of observed temperatures for volcanic areas on Io provides a simple way of separating the major components of infrared radiation coming from Io. Emission from the nonvolcanic, cold areas making up ~99% of Io's surface accounts for most of the flux in broadband measurements centered at 20 μm; the flux from volcanic areas with temperatures of 250 to 400 K dominates narrowband 8.7-μm measurements. Reflected sunlight with a small contribution from volcanic hotspots, primarily areas with temperatures ≳500 K, dominates the 4.8-μm spectral region. Because of these characteristics, the temporal and spatial variability of volcanic emissions from Io can be studied through measurement at several wavelengths of the total infrared flux from Io's disk as a function of time and orbital position (because Io is synchronously rotating, orbital position relates directly to the sub-Earth longitude on Io's surface).

Earlier studies of Io's thermal emissions

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have indicated that the behavior of the 4.8-μm flux has been distinctly different from that of the 8.7-μm flux. Johnson *et al.* (2) showed that during 1983 the 8.7-μm flux varied as a function of longitude by nearly a factor of 2; the highest fluxes were concentrated in the trailing hemisphere near 300°W longitude. They suggested on the basis of these data that the major source of emission was the large volcanic caldera Loki Patera, which is located at the longitude of the flux maximum and was identified by Voyager as the most powerful volcanic heat source observed during the 1979 flyby (*3, 4*). Similar observations made during each apparition since 1983 have showed that this general pattern in the 8.7-μm emission has not changed, although measurable changes in the flux levels have been observed at about the 20% level (*5*).

Observations of shorter wavelength radiation since 1979 have suggested that the higher temperature component of the volcanic flux has been more variable than the lower temperature component. Witteborn *et al.* (*6*) observed a large 4.8-μm anomaly even before the Voyager encounter, reporting a large increase in flux in infrared spectra taken between 4.7 and 5.4 μm on 20 February 1978. Sinton (*7*) observed a similar enhancement at 4.8 μm on one night between the two Voyager encounters; he attributed that event to an eruption in Surt caldera, which showed visible changes between the two encounters. Subsequent observations by Sinton and colleagues showed that the 4.8-μm flux was somewhat variable, in general, with occasional large outbursts (*8*). Only longitudinal variations in the 4.8-μm flux were evident in our data taken during 1983, 1984, and 1985. Such variations were consistent with the hot spots that were required to account for the 8.7-μm flux taken at the same time (*5*). In this paper we report observations of a significant volcanic outburst at multiple wavelengths from 4.8 to 20 μm (Fig. 1 and Table 1). These

Table 1. Magnitudes of infrared flux at 4.8, 8.7, and 20 μm (α-Lyrae equals 0 magnitude) for sub-Earth longitudes. All dates are 1986 UT; Long, longitude; Mag., magnitude.

4.8 μm		8.7 μm		20 μm*	
Long.	Mag.	Long.	Mag.	Long.	Mag.
		25 June			
321.6	3.62	313.6	0.63	312.9	−4.08
312.2	3.65	322.8	0.66	314.4	−4.00
314.0	3.59	315.1	0.62	322.3	−3.89
318.1	3.63	319.2	0.75	318.7	−3.89
		2 July			
302.4	3.46	302.0	0.69	302.7	−4.05
303.6	3.45	304.3	0.69	304.0	−4.06
307.1	3.46	307.8	0.69	307.4	−4.07
308.8	3.44	309.6	0.69	309.2	−4.08
315.6	3.49	316.4	0.70	315.8	−4.00
318.2	3.45	318.0	0.75	317.4	−4.03
318.7	3.46	319.7	0.71	319.1	−4.03
		320.2	0.72		
		3 August			
311.3	3.25	312.3	0.41	313.4	−4.01
314.1	3.25	315.1	0.42	316.4	−4.00
317.0	3.24	317.8	0.42	318.8	−4.05
324.5	3.26	328.8	0.47	330.5	−4.05
324.9	3.25	331.9	0.49	332.9	−4.10
331.0	3.24	337.4	0.53	338.4	−4.07
336.5	3.25	340.4	0.53		
338.9	3.25				
		4 August			
147.6	3.08	148.5	0.60	149.3	−4.29
149.6	3.12	151.0	0.61	152.0	−4.25
152.4	3.14	153.3	0.61	154.0	−4.22
154.3	3.15			156.1	−4.20
		5 August			
17.8	3.29	18.8	0.90	17.4	−4.02
20.1	3.29	21.0	0.91	19.8	−3.98
22.0	3.29	23.2	0.92	21.8	−3.99
27.3	3.27	28.4	0.92	27.0	−3.97
29.4	3.26	30.5	0.93	29.1	−3.94
31.6	3.26	32.6	0.94	31.4	−3.99
36.6	3.25	37.6	0.94	36.3	−4.03
38.7	3.25	39.7	0.93	38.3	−4.05
40.5	3.24	41.4	0.92		
		6 August			
202.3	3.18	203.3	0.75	201.9	−4.06
204.7	3.17	205.8	0.74	204.3	−4.12
207.2	3.18	208.1	0.74	206.8	−4.13
237.3	3.17	238.2	0.63	237.0	−4.23
241.7	3.16	242.7	0.60	241.3	−4.28
		7 August			
67.4	1.69	50.0	0.28	48.7	−4.08
79.0	1.85	54.4	0.27	53.3	−4.06
81.4	1.88	56.2	0.27	55.1	−4.09
85.9	1.94	79.9	0.24	67.1	−4.16
87.9	1.96	82.2	0.24	78.7	−4.19
		86.7	0.25	81.1	−4.18
		88.7	0.26	85.6	−4.16
				87.6	−4.17

*Monochromatic flux correction = 1.08.

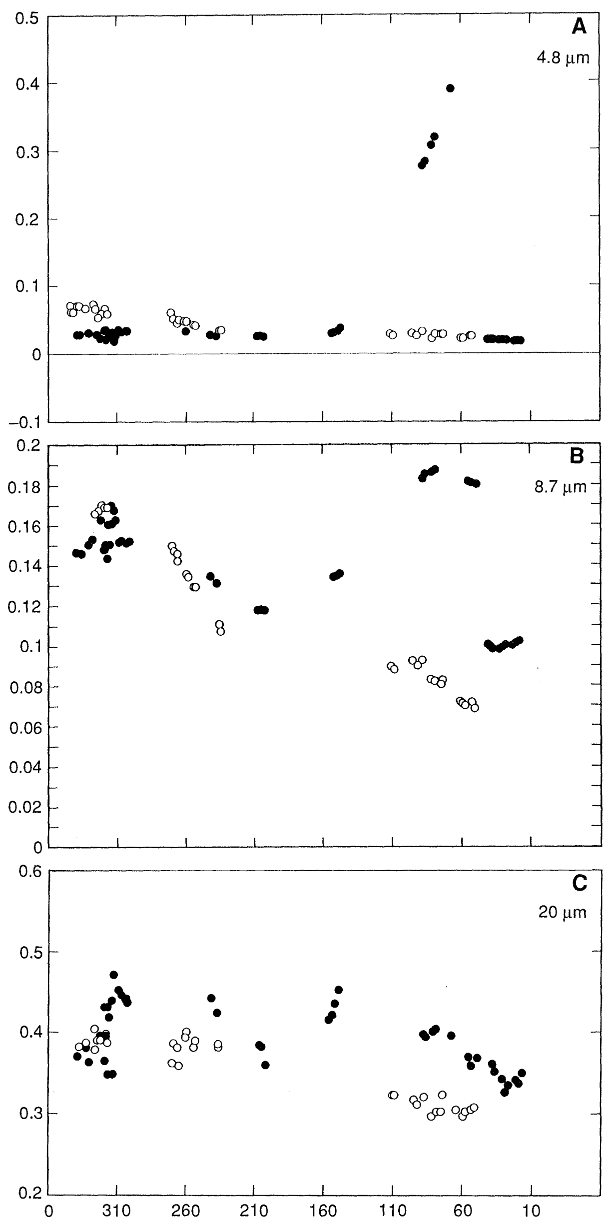

Fig. 1. Infrared flux from Io at 4.8 (**A**), 8.7 (**B**), and 20 μm (**C**) as a function of orbital longitude, which is equivalent to the west longitude of the sub-Earth point. We used specific flux to remove the effect of the variable distance of Io from Earth (watts per square meter per micrometer reduced to Io's surface for the case of isotropic emission from the entire surface). Data from 1983 are plotted as open circles [8.7- and 20-μm data are from (*2*)] and illustrate normal levels of volcanic emission; data from 1986 are plotted as filled circles. The elevated fluxes near 70°W at 4.8 and 8.7 μm are from 7 August (UT). The 4.8-μm data have had background flux from reflected sunlight subtracted (*9*).

Table 2. Model comparison; r, radius; T, temperature.

Model	Flux ($W\ m^{-2}\ \mu m^{-1}$)		
	4.8 μm	8.7 μm	20 μm
Observed flux excess	0.37	0.09	~0
(assumed base level)	(0.02)	(0.095)	(0.4)
r = 15 km, T = 900 K	0.37	0.096	0.006
r = 23 km, T = 715 K	0.36	0.132	0.01
r = 19 km, T = 715 K	0.24	0.09	0.007

Table 3. Comparison of events.

Event	Longitude (°W)	Latitude (°)	Radius (km)	Temperature (K)	Power (10^{13} W)	Comments
1978	68		26	600	1.6	(6)
Surt	338	45 N	25	600	1.4	(7)
			11	900	1.4	*
Pele	257	−19 S	6	654	0.12	(4)
Poliahu	83	−24 S	9	572	0.15	(13)
1986†	70		15	900	2.6	†

*Produces same 4.8-μm flux as in (7). †This study.

data allow us to constrain both the size and temperature of the source region and compare this event with earlier outbursts.

During the 1986 apparition, we made observations on seven nights using the Infrared Telescope Facility on Mauna Kea, Hawaii. The bolometer equipment, data system and observational techniques were the same as those described in (*2*).

The 1986 infrared flux levels at most longitudes agree well with earlier measurements, with minor variations attributable to changes in the levels of emission near the longitude of Loki and increased passive thermal background flux because of changes in Io's heliocentric distance. The data collected on the night of 7 August 1986 (UT) for sub-Earth longitudes between 50° and 89°W are clearly anomalous. The 20-μm flux showed no major change, but the 8.7- and 4.8-μm fluxes were both significantly enhanced over normal levels at these longitudes; the 8.7-μm flux was about two times normal and the 4.8-μm flux was about four times normal [an increase by a factor of 20 in volcanic emission when the reflected component is subtracted (*9*)].

Because measurements were made at several wavelengths over a range of longitudes during the night of 7 August, we can construct a simple model to constrain the size and temperature of the source responsible for the emission that night. The 8.7-μm data show little change over the 40° of longitude observed that night, which suggests that the source was near the center of Io's disk, probably located near 70°W (there is no way to constrain latitude from observations of this sort). If we take the observed flux excess above normal at 4.8 and 8.7 μm near 70°W longitude, a volcanic source on the surface at the equator with a diameter of 30 km and a temperature of 900 K gives a good fit at all wavelengths (Table 2).

This single source, single temperature model does not explain all the data. Such a source would produce similar changes in the 4.8- and 8.7-μm fluxes during the course of the observations as the projected area seen from the earth changed slowly. However, the 4.8-μm flux decreased rapidly during the course of the observation while the 8.7-μm flux remained relatively steady. The 4.8-μm decrease may have been the result of rapid radiative cooling of hot material exposed to Io's near vacuum (*10*). Depending on the composition of the melt, evaporative heat transport may also have been important (*11*). Simple cooling of a single temperature melt cannot account for both the 4.8- and 8.7-μm data; however, several temperatures or changes in the size of the source during the course of the observations, or both, may be required in order to model the event more accurately. We take the single temperature model fit as an indication that the observed event required a large source (radius ~15 km) and temperatures of at least 900 K. The event was also probably short-lived, on the basis of comparison with earlier outbursts and the suggestion of rapid cooling; observations showing that no significant leading side flux anomaly was present later in the apparition tend to confirm this conclusion (*12*).

The 7 August 1986 event was comparable in scale to the most powerful of other similar events (Table 3), including: (i) the 1978 event described by Witteborn *et al.* (*6*), where the model parameters were obtained from a spectral fit over a relatively small spectral range; (ii) the Surt event observed by Sinton (*7*), where only 4.8-μm data were obtained and the temperature was assumed from analogy with that of the 1978 event (*6*); (iii) the model parameters for Pele from Voyager observations (*3, 4*); and (iv) the Poliahu event detected during the mutual occultations of 1985 (*13*). The 1986, 1978, and Surt events are larger than either Pele or the Poliahu event. The model for the 1986 event suggests that during the outburst the power output from the source, $\sim 3 \times 10^{13}$ W, was greater than that from Loki, $\sim 1 \times 10^{13}$ W; however, the contribution from these events is small compared with the steady emission observed from the Loki longitude region because the outbursts are relatively infrequent and short-lived (*2*).

McEwen and Soderblom (*14*) suggested that high-temperature (for example, $\gtrsim$400 K) volcanism of the Pele type might be limited to the trailing hemisphere, on the basis of Voyager observations of Pele, Surt, and Aten and the association of these features with large deposits of the spectrally red material that dominates the longitude range centered approximately on Loki. For data collected before 1986, only the 1978 event indicated a high-temperature event in the leading hemisphere. The locations of two of the events in Table 3, Surt and Poliahu, are reasonably well constrained by the observations. The 1978 and 1986 events are located only by the approximate central longitude at the time of the event. Poliahu and both the 1978 and 1986 events all may have occurred in the same region of Io and could be associated with a single intermittently active feature, although this is not required by the data. The number of well-observed high-temperature events is not large enough to draw any conclusions about longitudinal distribution of this type of activity, other than that it evidently has occurred in both hemispheres.

We do not know whether the three well-characterized high-temperature events on the leading side share other characteristics of the Pele style of eruption in the trailing hemisphere. The Pele class events identified by McEwen and Soderblom (*14*) are associated with large eruptive plumes that create oval, low albedo, red patterns on the surface with diameters of 1000 km or more. If the leading side events were associated with similar plumes, they could have altered the global brightness and color pattern. Historical photometric data indicate that the pattern of brightness and color variations on Io had remained unchanged to within about 20% from about 1928 to 1979 (*15*). A careful study of Io's current photometric and spectral properties should be made to establish whether recent leading side volcanic activity has changed surface albedo and color patterns. No change in these patterns would indicate that high-temperature volcanism in the two hemispheres differs in the nature of the material ejected onto the surface by the events. On the other hand, a confirmed change would imply that high-temperature volcanism had been absent from the leading hemisphere for ~50 years and has just recently started or resumed. In either case, the unusually high temperature for the 1986 event may imply that there is another class of volcanic activity not directly related to earlier high-temperature events.

A major issue concerning volcanism on Io is the relative roles of sulfur and silicate melts in magmatic processes on the satellite. Shortly after the Voyager flyby, most workers focused on the role of sulfur compounds, principally S and SO_2, in producing the spectacular eruptive plumes, which were interpreted as S and SO_2 geysers (*16*). However, the amount of S in the upper crust of Io and the composition of the material in volcanic calderas and in flow structures surrounding volcanic centers remain unresolved questions. On the basis of the scale of both positive and vertical relief on the satellite, Clow and Carr (*17*) argued that silicates and silicate volcanism must play a major role in forming the topographic features of Io's surface; the high albedo and spectral reflectance of the surface indicate that at least a surficial layer of S-rich material and perhaps S lavas occur in some areas (*18*).

The temperatures inferred for the volcanic areas observed by Voyager and for earlier telescopic observations have all been below ~700 K. Temperatures near 700 K are compatable with molten sulfur, and lower temperatures could be produced by a cooler crust covering portions of the melt. A model of silicate volcanism on Io, again with a range of temperatures attributed to different degrees of cooling, has also been developed to match the infrared observations (*19*), and the previously reported temperatures cannot be used alone to distinguish between these two possibilities. The model temperature for the event reported in this paper, 900 K, is higher than that reported for previous events (*20*). Because the boiling temperature of S in a vacuum is 715 K, such a high temperature virtually rules out pure molten S as the major constituent of the magma in this eruption. A source temperature of 715 K and a size chosen to match the 8.7-μm data cannot account for the 4.8-μm data; similarly, if the size is adjusted to match the 4.8-μm data, the 8.7-μm data are not matched (Table 2).

If molten S is ruled out as the source of the 1986 event, what are the remaining possibilities? Some other S compounds with boiling points higher than 900 K, such as Na polysulfides (*11*), have been suggested as surface materials on Io or as constituents of lava lakes; eruptions of these materials could satisfy the data. However, given the other evidence for silicate volcanism in at least some places on Io and the virtual certainty that tidal heating produces molten silicates in the upper regions of Io's interior, we conclude that the high temperature of the event of 7 August 1986 is strong evidence for active silicate volcanism on the surface of Io. Molten S remains a likely candidate for other types of observed activity (as has been previously suggested), and the presence of SO_2 gas around plumes and on the surface (*3, 21*) and the escape of S and O into the magnetosphere of Jupiter indicate that S plays a major role in some of Io's volcanic activity. Silicate volcanism and S volcanism, whether primary or produced by remobilization during silicate eruptions, probably both occur at various times and places on Io.

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20. The temperature for the Surt event was originally assumed to be that determined from the spectrum of the 1978 event (*6*) observed by Witteborn *et al.*, (600 K), which was similar to the highest temperatures reported for Pele. If the temperature of the Surt event was 900 K, the radius of the source required to produce the observed 4.8-μm flux would be 11 km as opposed to the 25 km derived by Sinton (*7*) (Table 3). Such a difference in the presumed active area cannot be distinguished in the relatively low-resolution Voyager 2 images of the Surt area following the event. Thus, within the uncertainties, Surt could conceivably have had a temperature as high as that seen in the 1986 event.
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Effect of the Orbital Debris Environment on the High-Energy Van Allen Proton Belt

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Orbital debris in the near-Earth environment has reached a number density sufficient for a significant collisional interaction with some of the long-lived high-energy protons in the radiation belt. As a result of a continuing buildup of a shell of man-made debris, the lifetimes of high-energy protons whose trajectories remain below 1500 kilometers will decrease to the point where in the next decades we can expect a noticeable reduction in their fluxes.

INTRODUCTION OF MAN-MADE OBJECTS such as Earth-orbiting spacecraft, spent rocket casings, and other kinds of debris into the near-Earth environment has not only raised concern about the safety of astronauts but has also created the potential for permanently altering the near-Earth trapped radiation environment. I have used the National Aeronautics and Space Administration–Department of Defense (NASA/DOD) Civil Needs Database for orbital debris (*1*) together with moderate assumptions about future international space traffic to calculate lifetimes of high-energy protons (arbitrarily defined as protons with energy greater than 55 MeV) in the Van Allen radiation belt, subject to the assumption that in time the protons will collide with the particulate orbiting material and be absorbed by it. My results suggest that for low L values ($L = 1.2$ to 1.6) and high B_{mirror}

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