Volcanic Eruptions on Io:
Heat Flow, Resurfacing, and Lava Composition.

Diana L. Blaney, Torrence V. Johnson, Dennis L.Matson, and Glenn J. Veeder

Jet Propulsion Laboratory, California Institute of Technology

Submitted to Nature, June 13, 1994.
Pages: 15
Figures: 3

Key Words: Io, satellite, silicate, lava flow, eruption, infrared, radiometry, heat-flow, and volcano.

Correspondence: Diana L. Blaney
Mail Stop 183-501
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109-8099
Telephone: (81 8)-354-5419 FAX: (818}354-0966

*Visiting Astronomer at the Infrared Telescope Facility which is operated by the Institute for Astronomy of the University of Hawaii under contract from the National Aeronautics and Space Administration.

Volcanic Eruptions on Io: Heat Flow, Resurfacing, Lava Composition

Abstract

In this paper we consider the infrared outbursts on Io reported over the last 15 years and examine the implications for resurfacing rates and heat flow using a recent, well observed, eruption sequence[1], A large change was observed in Io's infrared emission on January 9, 1990 at several different wavelengths. We model this event as due to a large actively erupting lava flow. The flow increased its area at a rate of 1.5 x 105 m^2s^{-1} and cooled from 1225K to 555K over about 2.6 hours. This event is consistent with other Io infrared outbursts and is used in this paper to estimate the more general characteristics of Ionian volcanism, resurfacing, and heat flow. The inferred eruption rate of 3 x 105 m^3s^{-1} is very high, but is not unprecedented on the Earth. It is also similar to the high eruption rat es suggested for early lunar volcanism. Furthermore, the apparent frequency of eruptions, 6°/0, provides ample resurfacing to explain 10's lack of impact craters. The size and temperature distribution of the thermal anomalies derived from the Voyager IRIS data[2] and groundbased radiometry data[1] are consisten with our model of cooling lava flows, We suggest that the large radiometric heat flow, 10^{14} W, (obtained by both analyses), can be accounted for by a series of silicate lava flows in various stages of cooling. This eliminates the requirement that other fluids, such as sulfur, play a major role in transporting heat to Io's surface.

Introduction

The characteristics and frequency of the volcanic eruptions on Io, the innermost of Jupiter's four large satellites, are important for understanding 10's surface geology, internal structure, and heat flow, The source of the internal energy that drives Io's volcanic activity is Io's tidal interaction with

Jupiter which removes energy from 10's orbit and deposits it in the interior of Io[3,4]. The large amount of power radiated from Io, 1014 W[1,2], rules out any other known mechanism and is in fact so large that it is incompatible with existing steady-state models for tidal dissipation in 10[5].

Outbursts are characterized by large increases in 4.8 μm flux which suggest transient high temperatures (T>600K) over small areas, for short (hours to days) periods. While not common, several of these high temperature events have been observed since their discovery. An anomalous, large 4.$ μm flux on was also observed one night between the t wo Voyager encounters which was apparently correlated with a change in the albedo of the feature Surt[7]. Subsequently, other such outbursts have been reported[1,8,9,10,11]. In this paper we consider the outbursts observed over the last 15 years and examine the implications for resurfacing rates and heat flow using parameters derived from a well observed eruption*.

Multi-Wavelength Observations of Outbursts

Since 1983, we have been conducting a program of Io observations using the NASA Infrared Telescope Facility at four infrared bandpasses (4.8, 8.7, 10, and 20 μm). During this period two outbursts were measured and characterized[9,1]. The first of these events occurred on August 7, 1986 (UT) and is shown in Figure 1 (a,b). Data were collected during a five hour period at 8.7, 10 and 20 µm with additional data obtained at 4.8 µm during the last two and a half hours of the observations. The preliminary analysis of this event suggested that it could be modeled by the addition of a new volcanic thermal anomaly on Io's leading hemisphere with a radius of 15 km and a temperature of 900

K. The role of sulfur and silicates in Io's surface volcanism has been debated*[2,13,14]. However, the high temperature of this event compared with the boiling point of sulfur (715 K, STP) was interpreted as strong evidence for a silicate eruption as the source of the increased infrared flux and that at least some of the flows seen on Io are due to silicate lavas[9]. Subsequent analysis[1] via more refined models for the background emission from Io's surface suggests an even higher temperature (-1550 K and r = 8 km) which further strengthens this conclusion (Figure 1 (a,b)).

We observed a second event on the night of January 9, 1990 (UT). We measured this outburst for about 3 hours at all four of our bandpasses. This allowed us not only to derive the temperature of the source, but also to model the temporal behavior of the eruption. The data for 4.8 and 8.7 μm are shown in Figure 1 (c,d), reduced to spectral emittance versus the sub-Earth longitude on 10 at the time of each observation, The 20 μm flux changed little during this period. Since the observed quantity is the flux density from the whole disk of Io, a small constant emission source on the satellite's surface will produce a contribution which varies with time as the cosine of the difference in longitude between the sub-Earth point and the source's location. This is due to change in the projected area of the source as Io rotates (8.43 deg/hr). (see 1 for detailed reduction and modeling techniques for analyzing data of this type).

Our model for Io thermal emission is based on a distribution of thermal anomalies (from Voyager data where applicable) which matches the non-outburst data for the apparition. The spectral emittance from this model is shown as the "model" curve in each panel of Figure 1. The

1990 outburst observations start at a longitude close to that of Loki Patera, which a number of observations have shown to be one of the most prominent and apparently long-lived volcanic features on Io[15,16,17,18,19,20]. Infrared imaging observations made prior to our observing run showed that Loki was still the primary emission source at 3.8 and 4.8 µm and was more intense than usual in this spectral region[21]. Therefore, we model the source of this outburst as a new, high temperature anomaly at Loki's position. With this assumption, the data near the beginning of the observing sequence (7: 17 UT, 325° W longitude) were fit with a model source having a radius of 5.4 km and a temperature of 1225 K (the top curves in Figure 1 c and Figure 1 d).

This inital model fails to match the data set for either wavelength near the end of our observing sequence that night (10:03 UT, 348° W longitude), falling *above* the observed level oft he data at 4.8 µm and *below* it at 8.7 µm. Since the longitude of the source is not directly observed, we first consider the effects of uncertainty in the model source location. If the source were actually to the east of Loki, the 4.8 µm data could be fit with a single source size and temperature, but the discrepancy at 8.7 µm would be even greater than for the Loki source model; likewise, the 8.7 µm data could be better fit with a source to the west of Loki, making the match worse at 4.8 µm. We conclude that the characteristics of a source at the position of Loki changed during the course of our observations, and we fit the data toward the end of our observing sequence with a model source at Loki’s location with a larger radius of 22 km and a lower temperature of 555 K.

Second we consider the errors in the determination of the temperature and radii modeled for the January 1990 outburst. These are dependant on two factors: (1) photometric errors which can be estimated from the reproducibility of the standard stars during the night; and (2) the accuracy of the base 89-90 model curves in matching the nonoutburst data. We estimate the magnitude of these errors from the scatter of the data about the model curve on nonoutburst nights. The resulting uncertainty in the flux difference (outburst - nonoutburst) that the model matches for each wavelength is about 3°/0. Additionally, because our wavelength bandpasses are centered at 4.8 and 8.7 μm, we can more accurately determine temperatures around 500 K than those over 1000 K for the same magnitude of flux difference errors. Combining all of these factors we estimate that for the start of the outburst observation the derived temperature is 1225* 100 K, and the radius as 5.4 ± 1.5 km. At the end of our observations, our estimate is 555 ± 10 K and 22* 1.5 km.

Outbursts Statistics and Comparison with Other Data Sets

Outbursts can be characterized in terms of area and temperature, quantities which can be derived when observations are available for more than one wavelength. Figure 2 shows the area vs. temperature for all reported outbursts which were measured at multiple wavelengths. Isopower contours are also plotted in order to aid in the comparison of events. The two events from our program are shown as" 1986" and "1990". The 1990 model sizes and temperatures at the beginning and end of the night are connected by a line. The thermal anomaly at the site of the short lived Pele plume was characterized by IRIS on Voyager[15,16]. The Poliahu and "1985" points are from mutual occultation results[20]. These anomalies emit about an order of magnitude less power than the 1986 and 1990 outbursts. The cross labeled "1978" is from Witteborn *et al.*[6], while the solid line labeled Surt contains end points which match Sinton's observed 4.8 μm flux density for assumed temperatures of 600K[7,8] and 900 Kg. The other points (*) are from the 1979-1981 L' (3.8 μm) and M (4.8 pm) survey by Sinton *et al.*[8]. Two separate measurements on one particular night oft his survey are connected with a solid line. In examining this plot it is clear that at least half of these temperatures are inconsistent with molten sulfur as the lava (i.e., the boiling point of sulfur is 7 15K, at STP). Additionally, five observations ("1978", "1986", "1990", Surt, and one of the * points) have radiated power of ~1 0*^{3}W or greater. Therefore, the 1990 event is not anomalous in it's size or temperature when compared with the historical record of 10's eruptions. The characteristics of the 1990 event and it's implied eruption source are a good starting point to estimate the rate of volcanic resurfacing by lava flows on Io.

The frequency of these events can be estimated from the two monitoring programs. We observed outbursts on two nights out of 55, or 3.6% of the total nights from 1983 through 1993*. Sinton *et al.*'s[8] survey included 37 nights between 1979 and 1981 during which they observed 4 events at two wavelengths (-110/0) and 4 other less well characterized events, including Surt, for a total of ~22%. We conclude that in the last 15 years or so events of this sort were observable somewhere between 3.6 and 20% of the time, with the higher power level events being less frequent than the smaller events. Due to Io's 42.5 hour rotation period, a given hemisphere can be observed only every other night. On average, we observed for -3.2 hours per night so about 57°/0 of Io's surface was visible during the course of a night's observing.. Thus if events are short lived (less than

- a day), the actual frequency of eruptions is 1.7 x the observed frequency of 3 .6°/0, or 6°/0. We use this to estimate the frequency of outbursts in the greater than 10^{13} W power range, although the statistics are admittedly sparse.

Implications for Resurfacing

Qualitatively, a cooling, expanding thermal source is what one would expect from an active lava flow. We can calculate some of the characteristics of the January 1990 event from our fits at the beginning and end of the observation sequence and compare them with values estimated for terrestrial and other planetary volcanism. A simple calculation yields the rate of area] increase, 1.5 x 105 m^2s^{-1}. This rate is sufficient to completely resurface Io in -8.5 years if the "eruption" were continuous and the eruption vents distributed uniformly over the surface. If our observed event frequency is typical for geologically recent activity, then enough new area would be created to resurface Io in -142 years. We do not have a direct observational constraint on the geometry of the flow, but two rudimentary models which bracket the possibilities are a radially spreading surface and a rectangular source which increases in area by extending only its length. In the first case ,the circular flow front advances outward at a rate of-6.4 km hr^{-1} ; in the rectangular model R_{adv}, the rate of advance in km hr^{-1}, is given by the relation: R_{adv}= 156/w, where w is the width of the flow in km. Relatively fast rates, by terrestrial standards, are implied for even relatively large flow fronts (e.g., *55* km hr^{-1} for a 10 km wide flow), but are not unprecedented for fluid, high-eruption-rate events. Analysis of theHualalai flow of 1800-01 on the island of Hawaii[22] indicates that it's rate of advance was on the order of 35 km hr^{-1}.

Additional constraints on the resurfacing rate of 10 are: 1) the total lack of impact craters in Voyager images and 2) the amount of energy released in the resurfacing compared to the observed heat flow from Io. An analysis of the resolution and areal coverage of Voyager images suggests a globally averaged burial rate greater than 0.1 cm yr^{-1} if the cratering flux at Io is at least as large as for the Moon[23]. Reynolds *et al.*[24] noted that the energy required for resurfacing is a lower bound to the total heat flow. The minimum amount of energy required for resurfacing can be estimated from the heat lost in cooling the volume of erupted material from its liquidus temperature to the average surface temperature of Io (-100- 120 K). For silicate lavas this leads to a heat flow of greater than 7.5 x 10^{13} W for a resurfacing rate of 1.0 cm yr^{-1}. The infrared emission from Io's hotspots also provides a lower limit for the heat flow since our infrared radiometry is not sensitive to global crustal conduction. Analysis of our radiometric data and a recent reanalysis of Voyager infrared spectrometer data both yield heat flow estimates of greater than 10^{14} W[1,2]. A resurfacing rate of-1 .33 cm yr^{-1} of silicate lava could supply this amount of power. Thus, if we take our estimated rate of areal increase (assuming again that such events occur -6% of the time), an average flow thickness of -1.9 m would result in enough resurfacing to supply the observed heat flow. This is consistent with terrestrial basaltic lava flows which range in thickness from 1 to several 10's of meters[25,26]. Therefore, the observed power of 10^{14}W is consistent with production by known processes and our model rates for effusive volcanic activity.

Assuming that the flow thickness for the 1990 event was 1.9 m, then the eruption rate was -3 x 105 m^3s^{-1}. This is huge by most terrestrial standards; typical eruptions range from 10's to 100's of m^3s^{-1}[25,26]. Again the Hualalai flow provides a useful comparison. Recent modeling of this flow suggests an effusion rate of-105 m^3s^{-1}[22]. Also, the analyses of lunar flows yields similar rates[27,28]. If the long term frequency of outburst events is 6%, this corresponds to a total magma generation rate for Io of -550 km^3yr^{-1}, or more than 100 times the estimate for the Earth and 105 times that for the Moon, a body of the same size as 10[*9].

The resurfacing of Io by flows should result in a wide range of temperatures and areas for a large number of thermal anomalies, running from old, large cooling regions, to small currently active areas. Carr has modeled such a case for silicate flows to provide a match for the thermal spectrum from the Loki region observed by the Voyager IRIS experiment[14]. His calculation of the cooling of an active lava flow radiating to space yields a temperature drop from -1300 K to -500-600 K over a three hour period, in reasonable agreement with our event model which changed from 1225 K to 555 K in 2.6 hours. The observed cooling rate is also consistent with radiometric studies of active terrestrial flows[30]. Although highly simplified, the Carr model results in a local distribution of areas and temperatures that is quite similar in form to the characteristics of the (-10) anomalies required for an overall fit to our infrared radiometry of Io during the last decade (Fig. 3). Carr's areas need to be multiplied by 30 to scale to our anomaly distribution (equivalent to assuming that globally there are some 30 "Loki equivalents"). The eruption rate used in Carr's model was 3000 m^3s^{-1}, for a five year period, Thus the equivalent global average rate for 30 such sources is 9 x 104 m^3s^{-1}, compared with -2-6 x $10^4 m^3s^{-1}$ for a 6’% - 20% occurrence of flow activity similar to that observed in January, 1990. Considering the simplifications and uncertainties in the various calculations, this is reasonable agreement and suggests that the observed characteristics of Io's thermal anomalies could be due soley to multiple silicate eruptions. Although sulfur maybe mobilized by silicates, sulfur alone cannot account for the range of temperatures seen.

To assess the consistency of the observed hot spot distribution with resurfacing by multiple silicate flows we calculate that the total area of our modeled low temperature (150-200K) thermal anomalies (~ 2.8×10^6 km^2 or ~ 7% of Io's total surface area)[1] can be created in about 10 years if eruptions equivalent to the 1990 event are occurring 6% of the time. This is consistent with Cam's calculation that inactive flows cool to these temperatures in about 3-5 years under Io's conditions (see his Fig. 6). We propose that the whole suite of Io's currently observed anomalies can be produced by multiple, high-eruptive-rate silicate flows within the last century.

REFERENCES

1. Veeder, G. J., D. L. Matson, T. V. Johnson, D. L. Blaney and J. D. Goguen, *J. Geophys Res.*, in press, (1994).

2. McEwen, A. S., N.R. Isbell, K.E. Edwards and J.C. Pearl, New Voyager 1 hot spot identifications and the heat flow of Io, ***Bull. Am. Astron. Sot., 24, 935, (1992).***

3. Peale, S. J., P. Cassen and R.T. Reynolds, ***Science,*** 203, 892-894, (1979).

4. Yoder, C.F. , ***Nature, 279, 767-770, (1979).***

5. ***see*** Greenberg, R., in ***Time-Variable Phenomena in the Jovian System,*** edited by M .J. S. Belton, R.A. West and J. Rahe, 100-115, (NASA SP-494, Washington, D. C., 1989) for a review.

6. Wittebom, F. C., J.D. Bregman and J.B. Pollack, ***Science,*** 203, 643-646, (1979),

7. Sinton, W. M., ***Astrophys. J.,*** 235,L49-L51, (1980).

8. Sinton, W.M., D. Lindwall, F. Cheigh and W.C. Tittemore, ***Icarus, 54, 133-157, (1 983).***

9. Johnson, T. V., G.J. Veeder, D.L. Matson, R.H. Brown, R.M. Nelson and D. Morrison, ***Science,*** 242, 1280-1283, (1 988).

10. Howell, R.R., and W.M. Sinton, in ***Time-Variable Phenomena in the Jovian System,*** edited by M.J.S. Belton, R.A. West and J. Rahe, 47-62, (NASA SP-494, Washington, D. C., 1989).

11. McEwen, A. S., J.I. Lunine and M.H. Carr, in ***Time- Variable Phenomena in the Jovian System,*** edited by M.J.S. Belton, R.A. West and J. Rahe, 11-46, (NASA SP-494, Washington, D. C., 1989).

12. Smith B. A., E.M. Shoemaker, S.W. Kieffer, and A.F. Cook 11, ***Nature,*** 280, 738-743, (1979).

13. Sagan C., ***Nature, 280, 750-753,*** (1979).

14. Carr, M. H., *J. Geophys. Res.*, 91, 3521-3532, (1986).

15. Hanel, R. and the Voyager IRIS Team, ***Science,*** 204,972-976, (1979).

16, Pearl, J. C., and W.M. Sinton, in ***Satellites of Jupiter,*** edited by D. Morrison, 724-755, (University of Arizona Press, Tucson, 1982).

17. Johnson, T. V., D. Morrison, D.L. Matson, G.J. Veeder, R.H. Brown and R.M. Nelson, ***Science,*** 226, 134-137, (1984).

18. Goguen, J.D., and W.M. Sinton, ***Science, 230,65-69, (1985).***

19. Howell, R. R., and M.T. McGinn, ***Science,*** 230, 63-64, (1985).

20. Goguen, J. D., W.M. Sinton, D. L. Matson, R.R. Howell, H.M. Dyck, T.V. Johnson, R.H. Brown, G. J., Veeder, A.L. Lane, R.M. Nelson and R.A. McLaren, *Icarus,* 76, 465-484,(1988).

21. Spencer, J.R., M.A. Shure, M.E. Ressler, J.D. Goguen, W.M. Sinton, D.W. Toomey, A. Denault and J. West fall, ***Nature, 348, 618-621, (1990).***

22. Baloga, S. and P, Spudis, *XXIV Lunar and Planetary* ***Science*** *Conference,* ***55-56, (1993).***

23. Johnson, T. V., and L.A. Soderblom, in ***The Satellites of** *Jupiter*, edited by D. Morrison, 634-646, University of Arizona Press, Tucson, (1982),

24. Reynolds, R, T., S.J. Peale, and P. Cassen, ***Icarus,*** 44, 234-239, (1980).

25. Walker, G. P. L., ***Philos. Trans. R. Sot. London, Ser. A., 275, 107-118, (1973)*** and references therein.

26, Crisp, J. and S. Baloga, *J. Geophys. Res.*, 95, 1255-1270, (1990), and references therein.

27, Hulme, G. and G, Fielder, ***Philos. Trans. R. Sot, London, Ser. A. 285, 227-234, (1977).***

28. Head, J. W., and L. Wilson, ***Lunar and Planet.*** *Sci., XII,* ***427-429, (1981).***

29. Greeley, R. and B. D. Schneid, ***Science*, 254, 996-998,(1991).**

30. Flynn, L. P and P.J. Mouginis-Mark, *Geophy. Res. Let.*, ***19, 1783-1786, (1 992).***

ACKNOWLEDGEMENTS

The authors would like to thank Steve Baloga (JPL), David Piere (JPL), Joy Crisp (JPL), Barbara Bruno (U. of Hawaii), Peter Mouginis-Mark (U. of Hawaii), and Luke Flynn (U. of Hawaii) for helpful discussions about terrestrial volcanism. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract from NASA,

FIGURE CAPTIONS

Figure 1. Spectral emittance versus longitude (of the sub-Earth point) at 4.8 μm and 8.7 μm for the outbursts of August 7, 1986 (UT) and January 9, 1990 (UT) compared with model calculations. Available "non-outburst" data are also included. The thermal emission at 4.8 μm is plotted after removal of the reflected component. The curves labeled "model" correspond to the thermal anomaly model and non-outburst data for the entire apparition. The curves for the passive background at 8.7 μm are labeled as "background". The differences between the "model" and "background" curves are due to the emission from the thermal anomalies including the pedestal effect[1]. The curves labeled with values for "T" and "r" show the result of adding the thermal emittance from a hotspots of the indicated temperature and radius (located at 35° W for 1986 and at Loki (309° W) for 1990).

Figure 2. Log surface area versus log temperature for Io's well characterized outbursts. The cross labeled "1978" is from Witteborn e/ *al*[6]; and the solid line labeled Surt connects end points corresponding to temperatures of 600K[7,8] and 900K[9] for the 4.8 μm data of Sinton' . The other points (*) are from the 1979-1981 L' (3.8 pm) and M (4.8 μm) survey by Sinton ***et ala*** The Pele plume is characterized by IRIS on Voyager[15,16]. The Poliahu and "1985" mutual occultation results are from Goguen *et al.*[18]. The two events from Veeder *et al.*[1] are labeled as "1986" and "1990". Separate measurements on the same night are connected with a solid line. The diagonal lines are contours of constant emitted power (109 to 10^{14} watts).

Figure 3. Log surface area versus log temperature for Io's thermal anomalies. Hotspots for each apparition* are binned by 100 K increments and compared with results from McEwen *et al.*[2]. The areas (increased by a factor of thirty) and temperatures from Carr's[14] model calculations are also plotted. The diagonal lines are contours of constant emitted power ranging form 109 to10^{14} watts.

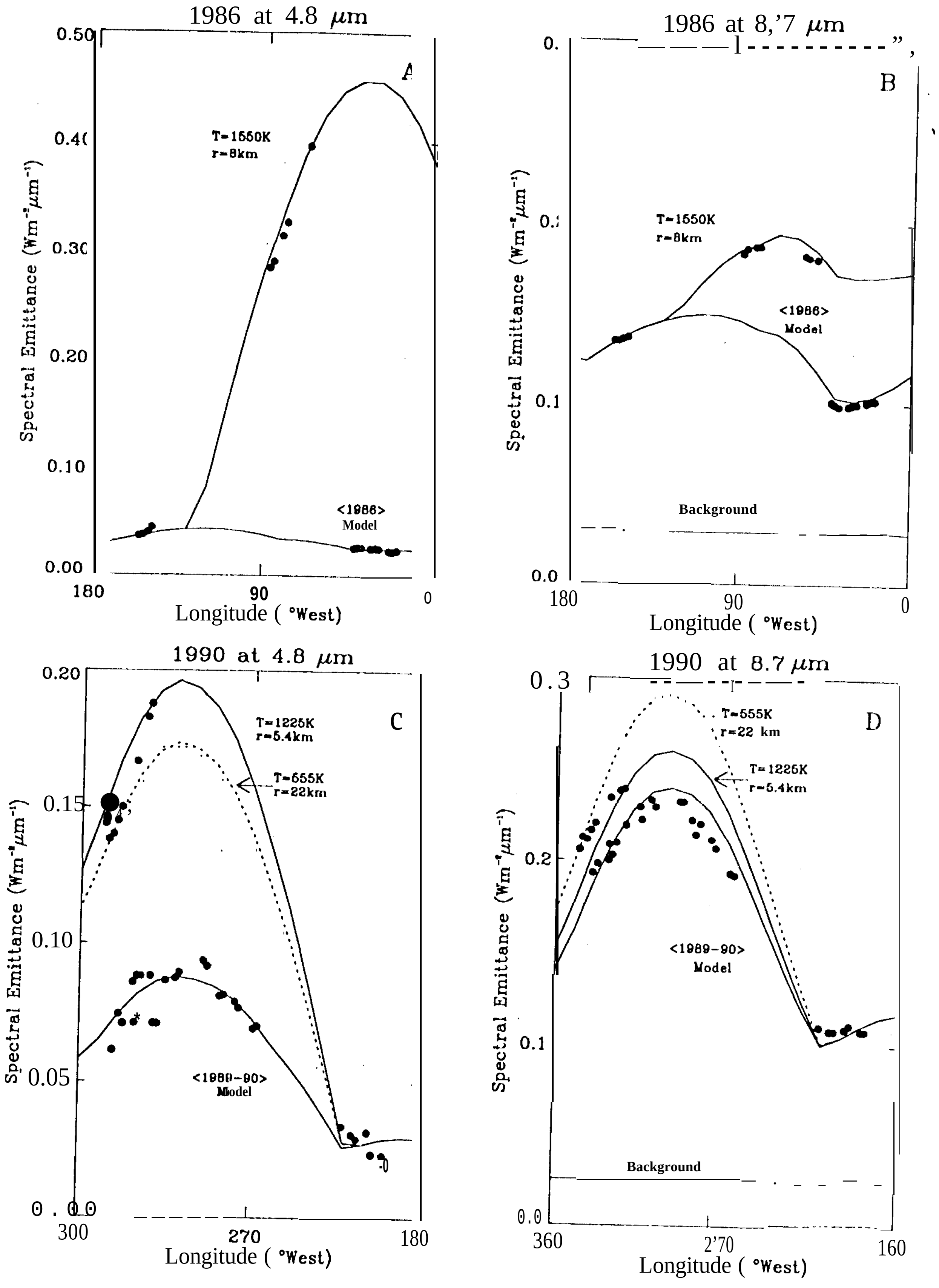
1986 at 4.8 μm
A
T=1550K
r=8km
<1986>
Model
Spectral Emittance (Wm$^{-2}\mu$m^{-1})
0.50
0.40
0.30
0.20
0.10
0.00
180
90
0
Longitude (°West)
1986 at 8.7 μm
B
T=1550K
r=8km
<1986>
Model
Background
Spectral Emittance (Wm$^{-2}\mu$m^{-1})
0.1
0.0
180
90
0
Longitude (°West)
1990 at 4.8 μm
C
T=1225K
r=5.4km
T=555K
r=22km
<1989-90>
Model
Spectral Emittance (Wm$^{-2}\mu$m^{-1})
0.20
0.15
0.10
0.05
0.00
300
270
180
Longitude (°West)
1990 at 8.7 μm
D
T=555K
r=22 km
T=1225K
r=5.4km
<1989-90>
Model
Background
Spectral Emittance (Wm$^{-2}\mu$m^{-1})
0.3
0.2
0.1
0.0
360
270
160
Longitude (°West)

Figure 2. Io Outbursts: Area vs. Temperature

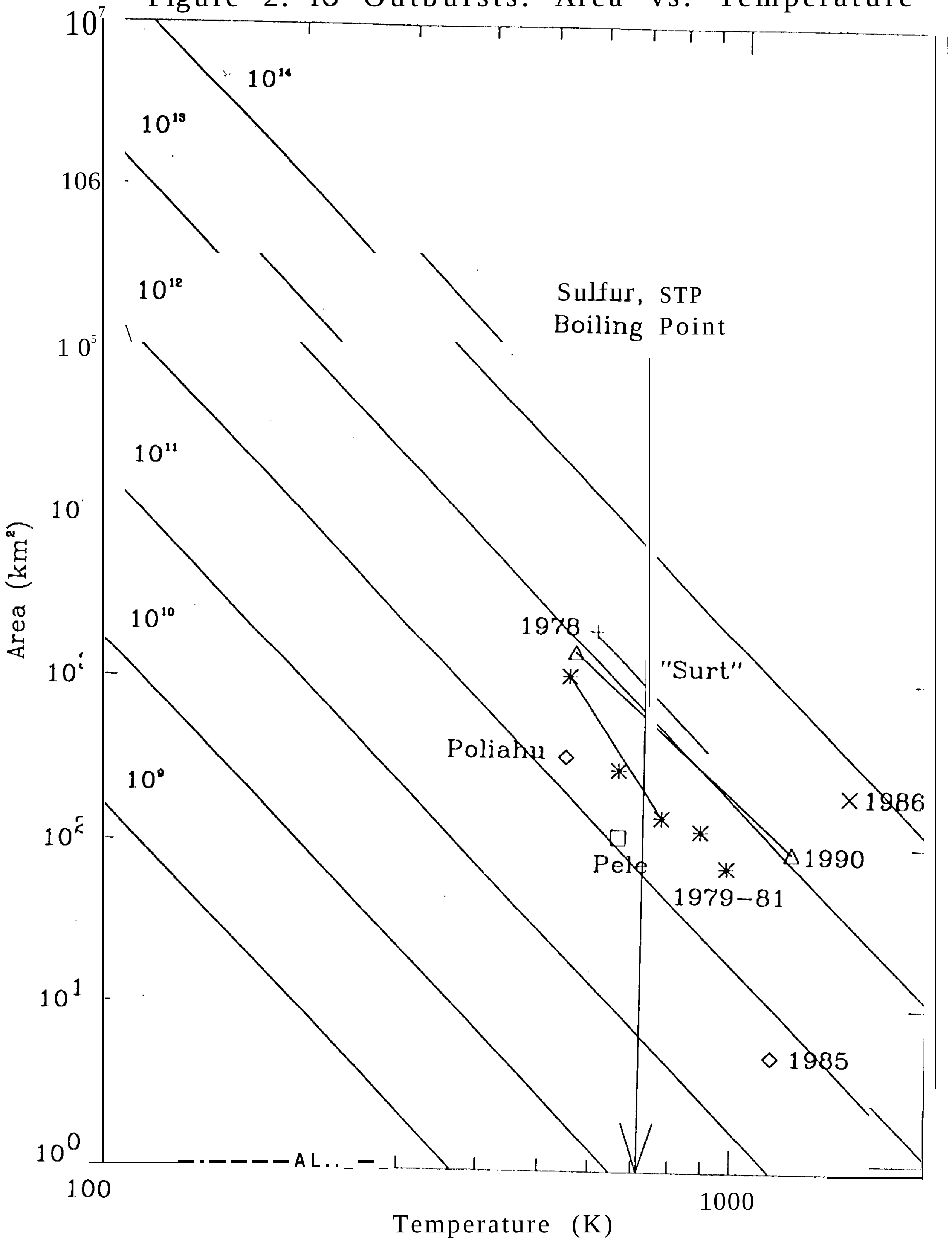

Figure 3. Binned Hotspots: Area vs. Temperature