Ground-breed Observations of Io

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Introduction

Ground-based observations are providing new information about the volcanic phenomena at 10's surface. Thermal emission from lava can be seen routinely at infrared wavelengths. One result of recent work is the reinvigoration of a familiar theme -- silicate volcanism. In the following paragraphs we will focus on such advances which have resulted from a better understanding of Io's thermal emission. This emission tells us about ongoing volcanic processes and heat flow. Io's total heat flow is especially important because of the tidal interactions among the bodies in the jovian system. The value of this heat flow not only constrains models for Io's interior but also those for Jupiter and for the long-term orbital evolution of the whole system.

It has beerr some fifteen years since the unambiguous detection of active volcanoes on Jupiter's innermost satellite Io by the Voyager spacecraft. The discovery of large geyser-like eruptive plumes and extensive lava flows on Io's bright, yellow-brown surface initiated a long running debate on the nature of the processes and the composition of the volcanic fluids. Remote sensing data suggested sulfur or sulfur compounds on the surface, and the Voyager infrared spectrometer (IRIS) detected $S0_2$ gas above a volcanic vent. Sulfur and $S0_2$ were proposed as the working fluids for the phase change volcanism driving the plumes. Sulfur liquid phases were also suggested as compositional candidates for the lava comprising the many lakes and flows evident in the images [Sagan, 1979]. On the other hand, strength and structural arguments and Io's relatively high density (3500 kg m^{-3}) were advanced as arguments for a major role for silicate volcanism [Carr *et* al., 1979].

Volcanic eruptions also provided an explanation for Io's unusual infrared spectrum and earlier, pre-Voyager, observations of short-lived, outbursts of infrared radiation. These are now interpreted as the result of varying levels of eruptive activity, Since the Voyager flybys, astronomical observers continued to measure Io's thermal emission at infrared wavelengths. They find that a large amount of heat is being radiated continually from a small number of volcanically heated regions on Io. Outbursts, or short-lived enhancements of flux from high temperature sources, while not common, have been observed since Witteborn *et al.*'s [1979] initial (pre-Voyager) measurement of a -600 K source. The second sighting was made by Sinton *et al.* [1980] who observed a large 4.8 μm flux on one night between the two Voyager flybys. It was suggested that this outburst was correlated with a change in the albedo and surroundings of the feature called Surt. Over the following years numerous "outbursts" were reported. They were all characterized by short periods (i.e., hours to days) of large increases in flux at 4.8 μm [Sinton *et al.*, 1983; Howell and Sinton, 1989; McEwen *et al.*, 1989; Johnson *et al.*, 1988; Veeder *et al.*, 1994b].

extensive data available, these assumptions turned out to be misleadingly simplistic approximations.

One compounding difficulty for the analysis of infrared data is the Earth's atmosphere. The key wavelengths for observing Io's thermal emission spectrum are from 2 to 30μm. Unfortunately, the atmosphere is not transparent over much of this range. Observation are confined to "windows" where the atmospheric transmission is high. This limitation on the accessible spectrum made it more difficult to discover faults in the emission models and probably prevented an early recognition of the significant role played by the thermal pedestal effect. The *thermal pedestal effect* is the spectral blue shift which occurs in the thermal emission spectrum when sunlight is absorbed on an anomaly whose temperature is elevated by heat flow [Veeder *et* al., 1994b]. Recognition of this shifting effect leads to the concepts of *active* and *passive* components of the background spectrum. The power in the background spectrum is entirely due to the re-radiation of absorbed sunlight. The spectra for passive components can be calculated a *priori*, given the necessary properties of the surface. By contrast, spectra for active components cannot be computed until after the temperatures of the anomalies have been specified. Depending upon the temperature of the anomaly, the peak of the active background spectrum can be shifted in wavelength by a substantial amount. In the case of 10, the thermal anomalies occupy only several percent of the surface. Accordingly, one would normally assume that sunlight absorbed on them would contribute negligibly to the observed thermal emission. In terms of total power, this is true, However, the spectral emittance at a specific wavelength can be greatly affected. At 8.7μm about 30% of the total observed radiation from Io is coming from these areas as a result of the thermal pedestal effect. At 4.8pm the corresponding amount due to the heating of the thermal anomalies by sunlight is -13 % of Io's thermal emission.

A second conceptual breakthrough was the realization that a significant amount of heat must be carried over to Io's nighttime hemisphere. Based on 10's rapid cooling in eclipse, earlier models assumed that Io's surface is very porous, with an extremely low thermal inertia --- similar to other airless solar system bodies but even lower. This class of model results in temperatures droping to very low levels at night. The use of this relatively "standard" airless body model effectively blocked the consideration of models which could retain significant amounts of heat to be radiated later, long after local sunset. New data and the recognition of the thermal pedestal effect forced a reconsideration of these ideas. Significantly, it was discovered that the thermal pedestal effect can mimic some aspects of the temporal signature of the eclipse of a very low thermal inertia surface. As a consequence of this, it is now realized that the presently available eclipse-cooling measurements for Io place no useful constraint on thermal inertia.

The first of the new generation of models involves three types of surface units: 1) a relatively low albedo unit which is in instantaneous equilibrium with sunlight and contributes the fall off in emission when Io enters eclipse; 2) a high albedo thermal reservoir unit which contributes significant levels of thermal emission during the nighttime, and 3) the volcanic thermal anomalies. The reservoir, of course, has a very high thermal inertia. The other units are assumed to have relatively low inertias, allowing them to be in approximate equilibrium with sunlight. The three thermal units, in turn, actually produce five distinct spectral components: the emission due to radiation of absorbed sunlight for each of the three units, the emission due to heat flow, and reflected sunlight which is significant at shorter wavelengths, such as 4.8μm. The equilibrium and reservoir thermal units are assumed to be interspaced uniformly over Io's disk (except at the sites of thermal anomalies). The anomalies, which are at specific locations, occupy several percent of the surface [Veeder *et al.*, 1994 b].

How well is the new modeling approach working? It successfully predicts the observed fluxes. At some wavelengths (e.g. 20μm) the discrepancy previously had been more than a factor of two. Now the agreement between model and observation is about ten percent over the range of 5 to 20pm. Consequently, the model parameters, including temperature and size, for the thermal anomalies are now more accurately known. The temperature at which an anomaly can be recognized has been lowered from about 300 K *to* a little less than 150 K. This, in turn, allows greater accuracy in calculating the heat flow from the global ensemble of thermal anomalies. Significantly, the areas and temperatures required by the new model based on telescope radiometry are in good agreement with a new independent analysis of spatially resolved spectra from the Voyager IRIS [McEwen *et al.*, 1992].

Outbursts on Io

With better data now available for thermal anomalies, Io's outbursts have again become a promising avenue for future progress. The outburst data are plotted in Fig. 1. Most of the data lie above the boiling Point of sulfur and, therefore, require silicate lava. Recently a detailed analysis has been carried' out on the 1990 event [see Veeder *et al.*, 1994a,b; Blaney *et al.*, 1994]. Such large outbursts (i.e., 10^{13} W or larger) are estimated to occur about 6 % of the time [Blaney *et* al., 1994]. The uncertainty in this estimate, however, is large. In the 1990 event the source area increased at a rate of 1.5 x 10^5 m^2 s^{-1}. If this growth continued unabated it would equal the whole surface of Io in -8.5 years. With a 6% frequency of occurrence, this becomes -142 years. If one assumes that all of Io's thermal anomalies are due to similar flows but in various singes of cooling, then the spreading rate taken together with the heat flow constrains the average flow thickness to be -1.9 m. The corresponding effusion rate is -3 x 10^5 $m^3 s^{-1}$. This is huge by terrestrial standards. However, recent modeling of the 1800-01 Hualalai flow on the island of Hawaii finds an effusion rate of - 10^5 n? s^{1} [Baloga and Spudis, 1992]. Also there are examples larger effusion-rate flows on the Moon [see Hulme and Fielder, 1977]. Therefore Io's outbursts fall within the bounds of our experience. These examples may serve as useful guides for developing an understanding 10's flows.

Future Developments

At the time of this writing the superbly instrumented Galileo spacecraft is approaching Jupiter. Galileo is expected to establish the definitive reference data set for Io. Undoubtedly, a variety of new volcanic phenomena will be revealed. Thus, we will not have to wait long before there will be another improvement in our understanding of Io. Since many of the processes involved in Jovian-system's tidal interactions and in the resurfacing of 10 have long time scales, continuing ground-based observations of Io's volcanic activity will be worth doing long after the end of the Galileo mission. Examples of such observational programs include images from the Hubble Space Telescope [e.g. Sartoretti *et al.*, 1994] and earth-based infrared observations [e.g. Spencer *et* al., 1992, 1990; Veeder *et al.*, 1994] and occasional, special viewing opportunities such as the 1991 mutual occultations and eclipses of the Galilean satellites [e.g. Spencer *et al.* 1994] will allow continued monitoring of Io's volcanic activity during and beyond Galileo era.

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Figure Captions:

Figure 1. The data for IO's better characterized outbursts is plotted as log(surface area) vs. log(temperature). The diagonals are lines of constant radiated power in W. Significantly, most of the data are at temperatures higher than the boiling point of sulfur, indicated by the long vertical arrow. (This figure is from Blaney *et al.* [1994]. The cross labeled "1978" is from Witteborn et *al.* [1979]. The end points of the "Surt" line connect the 600 K [Sinton *et al.*, 1980] and the 900 K [Johnson et *al.*, 1988] analysis of the 4.8μm data of Sinton *et al.* [1980]. The "*" data are from the 1979-1981 survey by Sinton *et al.* [1983], with a line connecting observations made on the same night. "Pele" is IRIS data [Hanel *et* al., 1979; Pearl and Sinton 1982]. "Poliahu" and "1985" are from Goguen *et al.* [1988]. "1986" and "1990" are from Veeder *et al.* [1994].)

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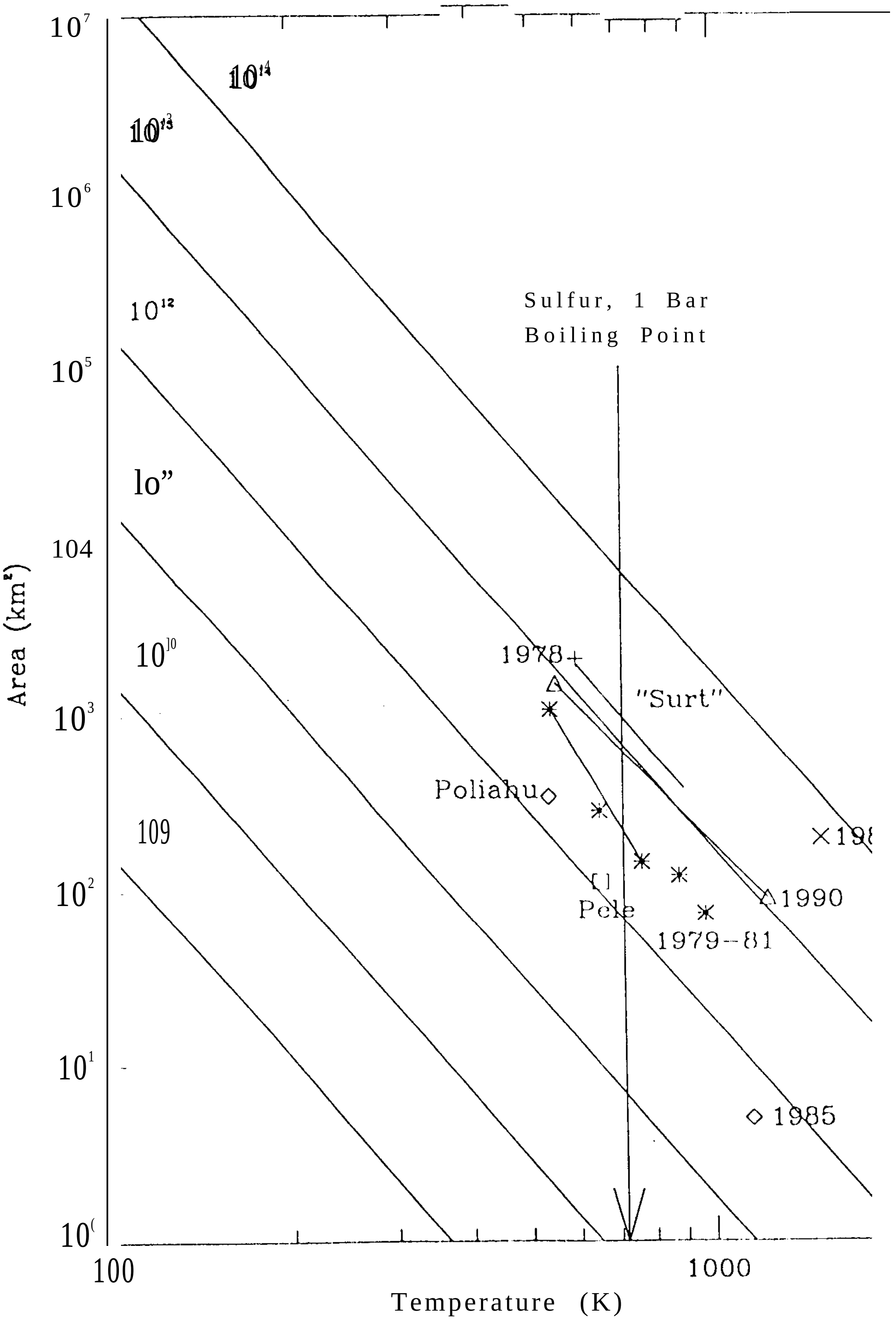

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