Overview: Voyager 1 IRIS spectra of Io from 4- to 55 μm wavelength have been further analyzed. We report two advances here: improved pointing corrections for the IRIS observations and improved background thermal models. The pointing corrections allow detailed mapping of thermal anomalies relative to surface features, thus enabling improved geologic interpretations. The background models are of critical importance to the identification of low-temperature (T) thermal anomalies due to cooling flows and pyroclastics, and to determination of Io's heat flow. The background T's also provide important constraints on models of Io's atmosphere and volatile transfers. A new model for Io's surface that has emerged from this and other studies includes 3 basic thermophysical units: (1) bright, SO2-rich regolith with a high thermal inertia over ~80% of the surface; (2) darker, SO2-poor regolith with a low thermal inertia over ~18% of Io; and (3) high-T hot spots over ~2% of the surface. We present new evidence that unit 2 contains ubiquitous low-T geothermal anomalies from cooling volcanic deposits.

Background: In 1979 the infrared interferometer spectrometer (IRIS) on the Voyager 1 spacecraft observed individual thermal anomalies on Io from about 4- to 55-μm wavelength (180-2500 cm⁻¹) [1]. The circular field-of-view (FOV) has a diameter of 0.25°. IRIS FOVs 50 to 700 km in diameter covered about 30% of Io's surface. Nine major hot spots were initially identified from IRIS data [2], and 13 additional hot spots have been identified in subsequent studies [3-6]. All except low-T (< 250 K) hot spots probably correspond to low-albedo surface features [7]. Most or all of the major hot spots are associated with caldera-like structures, and some correspond to lava flows. Many low-T anomalies are associated with recent flows with especially dark and reddish spectral properties. All of the IRIS observations over active volcanic plumes revealed hot spots.

IRIS Pointing Corrections: The IRIS pointing solutions have been improved via use of two datasets: geometrically-controlled Voyager images and JPL's image pointing file (IPF). The IPF is a record of the expected camera pointing angles (right ascension and declination) on 4 s intervals, and was derived from the spacecraft engineering data used also to generate the SEDR (Spacecraft Experimental Data Record). IRIS is boresighted to the imaging system, with a small (but known) offset. The IRIS pointing information in the SEDR has never proven very satisfactory, resulting in typical errors of up to tens of degrees. The SEDR has a similar accuracy for the imaging observations, but features in the images themselves have been used to construct control networks and updated pointing angles, reducing the errors by several orders of magnitude [8]. Therefore, our basic problem is how to use the updated pointing information for the images to improve the IRIS pointings. This problem would be trivial if each IRIS interferogram peak was nearly simultaneous with an image shuttering, but the interferogram peak was offset 24 s from the shutter times to avoid possible vibrational noise [9], and interferograms were acquired more often than images. IRIS spectra were acquired every 48 s during the Io flyby, and images were typically acquired either every 96 s with the narrow-angle (NA) camera, or with alternate wide-angle (WA) and NA frames every 48 s. Scan-platform slews to new pointing positions were initiated immediately after shutter close of a NA frame. Therefore, the IRIS spectrum acquired just before a NA image is shuttered will typically have nearly the same pointing as the image, and each spectrum acquired just after a NA image will typically have a very different pointing geometry. The entire set of useful Voyager 1 images have been geometrically controlled at RAND Corporation [8]. We have derived new T-area models for each of about 400 IRIS spectra of Io by minimizing the chi-squared statistic over each spectrum from 200 to 2400 cm⁻¹, but excluding the noisy region from 690-800 cm⁻¹ [10].
TEMPERATURES ON IO: McEwen et al.

An average reflected flux was subtracted from daytime spectra, a very minor correction. The noise equivalent spectral radiance, derived from a large number of deep space spectra recorded near Jupiter, was input as the standard deviation at each wavenumber. Model fits with two and three fractional areas and corresponding Ts were derived for assumed emissivities varying from 0.5 to 1.0. The smallest chi-square value resulted from unit emissivity for all spectra except those with "contamination" from space, in which case the best-fit emissivity actually represents a model fraction of the FOV filled by Io, biased somewhat by non-uniform sensitivity across the FOV [9]. Most fits to the data are excellent (chi-square less than 2 or 3), and there is no evidence for non-unit emissivity at 20 μm as previously suggested [11].

Nearly all of the IRIS observations require at least a two-T model to adequately fit the spectra; three Ts are required when there is an energetic or high-T hot spot. Typically, about 70-99% of the field-of-view (FOV) is modeled with a T from about 80 to 120 K and about 1-30% of the FOV requires a 50 to 90 K higher T. Contrasts of up to tens of degrees can be produced by albedo variations, topographic roughness, thermal inertia variations (including insolation propagation [12]), or low-T geothermal anomalies.

Significant progress in understanding Io's passive thermal behavior has resulted from analyses of eclipse observations [13,14], which can be modeled with 3 major surface units: (1) bright areas with a high thermal inertia covering >80% of Io; (2) dark areas that maintain close to instantaneous equilibrium with solar insolation over 18% of Io; (3) obvious hot spots over 2% of Io. Hence, ~18% of Io's surface reaches much higher daytime Ts because of a combination of lower albedo and low thermal inertia. However, there is also evidence for widespread low-T geothermal anomalies on Io. The most straightforward evidence comes from the IRIS nighttime observations. During the nighttime unit 2 should be 50 K cooler than unit 1, so it cannot be confused with geothermal enhancements. Nearly all of the IRIS nighttime spectra nevertheless require significant (>20 K) enhancements over 1% to 15% of each FOV. Apparently, low-T geothermal hot spots are ubiquitous, usually occurring within any spot down to at least 50 km diameter. The low-T geothermal anomalies seem to be concentrated in unit 2 because (1) low-T anomalies in daytime spectra are concentrated over relatively dark surface features; (2) these dark features often appear to be relatively recent volcanic deposits such as flows; and (3) the elevated Ts should remove the bright SO₂ frost via sublimation.

With the improved IRIS geometric information we can accurately determine background Ts as a function of latitude and local time-of-day. We plotted the lowest Ts for each spectrum as a function of local time and normalized for latitude, and excluding spectra with emission angles exceeding 45° (to minimize emission-angle effects and avoid possible contamination by space). We have no choice but to use the SEDR pointing information for the nighttime spectra, but they show a nearly constant T of 90 ± 5 K. Daytime Ts increase to about 120 K, with the peak Ts clearly occurring in the afternoon. Compared to the expected thermal equilibrium behavior, these daytime Ts are much lower and the nighttime Ts are much higher. However, the Ts are not a constant 109 K day and night as modeled in [14]. The insolation-propagation prediction of Brown and Matson [15], with absorption over a depth of 1.5 cm, provides an excellent fit to the data. Note that the shape of the diurnal curve suggests that the evening terminator over bright (SO₂-rich) regions will be ~25 K warmer than the morning terminator, an important consideration for Pioneer and Galileo radio occultation profiles. The diurnal T curve also has implications for the sublimation- or plume-driven flow of SO₂ [16].

How much of the daytime T enhancements in unit 2 is due to passive versus geothermal mechanisms? We plotted these Ts versus solar illumination angle for IRIS spectra that require only 2-T fits (and thereby avoiding the most energetic or high-T hot spots). Also shown is the expected T curve for the equilibrium thermal unit with an albedo of 0.29 [14]; this curve just brackets the lowermost data points. We interpret the enhancements over the model curve to be due to geothermal heat; this interpretation satisfies a couple of consistency checks. This interpretation implies that geothermal heat contributes to the Ts over ~20% of Io's surface; if this were not the case these areas would rapidly equilibrate to the thermal behavior of the brighter 80% of the surface due to the preferential condensation of SO₂ frost at night.

Io's heat Flow in 1979: We can estimate the minimum heat flow of Io from the power above background of the 25 most energetic and largely non-overlapping IRIS FOVs, which is 2.9 x 10¹³ W. Since IRIS covered ~31% of Io with the spectra analyzed here, we can extrapolate to the global heat flow by assuming that the region covered by IRIS is typical except for Loki; this gives a total minimum power of 7.6 x 10¹³ W, or 1.85 W m⁻² as a global average heat flow. Io's actual heat flow must be significantly higher due to conducted heat, many warm deposits in between the 25 most energetic FOVs, and geothermal contributions to the lowest-T areas (assigned entirely to background here). We expect that the actual heat flow exceeds the theoretical upper limit to steady-state tidal heating, 9 x 10¹³ W, as concluded previously [6, 14]. The best estimates for Io's global heat flow will be achieved by applying a realistic background model to the 10-year monitoring dataset of Veeder et al. [14].