ICARUS 60, 685–700 (1984)

Sulfur Flows of Ra Patera, Io

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Received August 26, 1983; revised May 14, 1984

Voyager 1 imaging data have been used to investigate the color and morphology of several radial flow-like features at Ra Patera, a broad volcanic structure at approximately 8° latitude and 325° longitude on the Galilean satellite Io (J1). It was found that downstream progressions of flow color and morphology are consistent with lava of a predominately sulfur composition cooling radiatively and erupting in the range of 470 to 520°K at effusion rates at 10^{10} to 10^{11} cm^3/sec. This implies global resurfacing rates by volcanic flows on Io of the order of 1 cm/year. Calculated energy content and effusion rates for flows at Ra Patera, using the physical parameters of sulfur, are of the order of the largest known terrestrial basaltic eruptions and are consistent with calculations of globally available energy.

INTRODUCTION

The discovery of volcanic plumes and flows on Io by Voyager, the development of models for intense tidal heating of Io (Peale *et al.*, 1979; Smith *et al.*, 1979a,b; Morabito *et al.*, 1979), and the strong evidence for the presence of sulfur in the vicinity of Io (Kupo, 1976; Broadfoot *et al.*, 1979) and on its surface (Wamsteker, 1972; Nash and Fanale, 1976; Nelson and Hapke, 1978; Soderblom *et al.*, 1980) give credence to the hypothesis of Ionian sulfur volcanism (Sagan, 1979; see also Schaber, 1980).

We offer the hypothesis that progressive color and morphology changes in flows at Ra Patera indicate a sequence of sulfur allotropes within the flows. For the flows studied we have found that the morphology and color sequences are consistent with a predominantly sulfur lava erupting in the range 470–520°K at effusion rates of 4×10^{10} to 10^{11} cm^3/sec. Further, if at least one feature like the longest flow at Ra Patera is active continually, we predict mean resurfacing rates on Io by volcanic flows alone to be on the order of 1 cm per year. This rate is substantially in excess of the rate required to erase potentially visible impact craters (10^{-1} cm/year; Smith *et al.*, 1979), and is much greater than the minimum resurfacing rate inferred for the Ionian plumes (10^{-3} cm/year; Johnson *et al.*, 1979). Thus, volcanic flows, either entirely or mainly composed of sulfur, may be the most active resurfacing agent on Io.

The general properties of sulfur have been reviewed extensively elsewhere (e.g., Meyer, 1976). On Earth sulfur has occurred as a lava only infrequently. However, there exists a fascinating account (Watanabe, 1939) of a large eruption of remobilized sulfur (the Japanese word for which, incidentally, being "Io") on the island of Hokkaido. Other small eruptions, both subaerial and subaqueous (Colony and Nordlie, 1973; Bennett and Raccichini, 1978; Francis *et al.*, 1980) have been documented, but sulfur effusion is generally more often associated with fumarolic activity.

The behavior of sulfur lava can be markedly distinct from typical silicate lava (Table 1). Most striking is the decrease in vis-

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0019-1035/84 $3.00

TABLE I

COMPARISON OF THE PROPERTIES OF SULFUR AND SILICATE LAVAS

	S-Lava	Si-Lava
Composition	Various allotropes and polymers of sulfur	Complex ferromagnesium silicates
Effusion temperature	392 to 700°K	1200 to 1600°K
Viscosity	10 cP at 425°K 10^4 cP at 500°K	10 to 10^{15} cP over a broad range of compositions and temperatures
Color	Variable according to temperature, phase, and cooling history: black, red, orange liquid or glass; yellow or white solid; presence of organic contaminants inhibits allotropic color changes	Black to dark red, depending on amount of oxidized iron
Occurrences	Possibly ubiquitous on Io; rare on Earth; unknown elsewhere	Ubiquitous on terrestrial planets, possible on Io's surface

cosity of molten sulfur at about 435°K (Fig. 1), which suggests that a hot sulfur lava flow would change from a fairly slowly moving mass (viscosity ~10^4 cP) to a low viscosity (~10 cP) fast-moving flow; the rapid decrease in viscosity could cause major portions of the flow to accelerate and become thinner resulting in thin sheets of low viscosity sulfur emanating from sinuous high viscosity flows closer to the vent (Pieri *et al.*, 1981; Sagan, 1979).

Another distinct property is the color change reported as sulfur cools through a sequence of allotropes (Meyer, 1976). Although the color of sulfur is in reality a continuum, we have designated for the purpose of discussion color transitions to occur at roughly 494°K (black to red), 444°K (red to red–orange), 434°K (red–orange to orange), and 406°K (orange to yellow). The use of such color names in this paper is for notational convenience only, and does not imply vivid or saturated hues. The "red–orange" allotrope designation is used here to refer to the zone of steepest descent on the temperature/viscosity diagram, in transition between the high viscosity red and low viscosity orange allotropes. In laboratory investigations allotropic colors in the liquid are reported to have been preserved upon quenching and retained for substantial periods of time (Meyer, 1976). There is, however, major disagreement among investigators over the nature and effectiveness of the color preservation mechanism across a range of conditions, and in our experience, even for very small (10–100 g) amounts of liquid sulfur, it has been difficult to quench allotropic colors (see, e.g., Nelson *et al.*, 1983). Nevertheless, as we will show below, the flows at Ra Patera appear system-

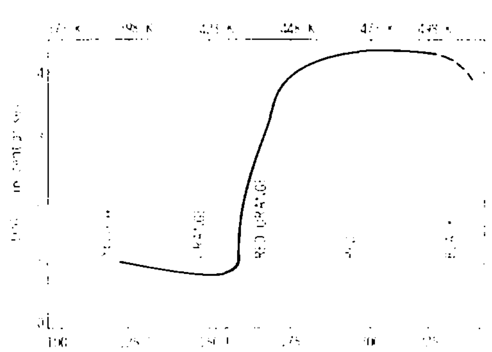

FIG. 1. A representation of the viscosity of sulfur as a function of temperature (adopted from Sagan, 1979, and Weast and Astle, 1982). Note the rapid drop in viscosity over the temperature range 444°K to 434°K. This transition zone is designated here as representing the behavior of the "red–orange" sulfur allotrope.

atically variegated in color, with spectral signatures consistent with a sulfur composition.

This paper deals specifically with interpretations of features at Ra Patera in the context of the sulfur lava hypothesis (Sagan, 1979), as combined with subsequent thermal modeling (Baloga *et al.*, 1981), and geological observations (Pieri *et al.*, 1981). We have utilized both qualitative and quantitative color analyses in this paper. Qualitative analyses were carried out using Voyager images produced by the Image Processing Laboratory at the Jet Propulsion Laboratory. Enhanced images of the Ra Patera complex with correct relative colors were used. This data set was useful for photogeological mapping and for measurements of physical dimensions (Figs. 2A and B). A complementary quantitative data set was also constructed using transverse scans of individual picture elements (Figs. 3A–C) at a series of locations along all three Ra Patera flows. This data set was used for intra- and interflow color comparisons. Every effort was made to use the most current decalibration files available for the Voyager high resolution image data (Danielson *et al.*, 1981).

DATA AND OBSERVATIONS

Ra Patera is a broad structure at approximately $-8°$ latitude and 325° longitude (Fig. 2A), exhibiting a range of flow morphologies emanating radially from a dark roughly circular central region, which is probably a volcanic caldera (Greeley *et al.*, 1983). No apparent active plume volcanism at Ra Patera was observed during either of the Voyager encounters with Io.

We examined the geomorphology and spectral properties of three well-expressed flows at the Ra Patera complex. For the sake of reference we have designated them as Main Flow, Middle Flow, and Upper Flow (Fig. 2A). Their respective lengths are 313, 165, and 147 km. Widths for Upper and Middle Flows are about 5 to 8 km. Both flows are sinuous, with sinuosity wavelengths of the order of 25 km and amplitudes of about 5 km. The Main Flow is somewhat more complex. For the 70 km nearest to the caldera, the flow is relatively straight and about 10 km wide. At about 70 km from the edge of the dark caldera, the flow narrows and becomes sinuous, while at 150 km from the caldera, the flow exhibits a decreased sinuosity and becomes wider (10–20 km). The most distal reach of the Main Flow, beyond 190 km from the edge of the caldera, is markedly distinct. Here the morphology of the flow changes from that of a relatively confined and directed feature to a broad (50-km wide) zone with less well-defined margins. Both the Middle Flow and the Upper Flow appear to be monofilaments, while the Main Flow appears ramified with re-entrants in its middle sections. Margins of all three flows appear to be well defined and crenulated with minor invaginations, and in all Voyager filters contrast strongly in albedo with a much lighter substrate, except for the distal part of the Main Flow which appears much brighter (in all Voyager filters) than more proximal reaches. Along all of the flows, the flow centers inevitably appear darker than flow margins, with the exception of the broad bright distal reach of the Main Flow.

Other deposits also originate from the same caldera. These are wide (25–40 km), bright features which cover substantial areas ($\sim 5 \times 10^4$ km^2). They abut pre-existing topography (e.g., old calderas and flows), and in a few cases preexisting albedo features may show through weakly, indicating that some of these deposits may be relatively thin. These features may represent plume deposits, although they generally look more like flows. Greeley *et al.* (1983) suggest that such features may consist of flows mantled by plume deposits.

Since the question of color is so central to discussion of potential sulfur volcanism on Io, we systematically investigated the reflectivity of the Ra Patera flows and cal-

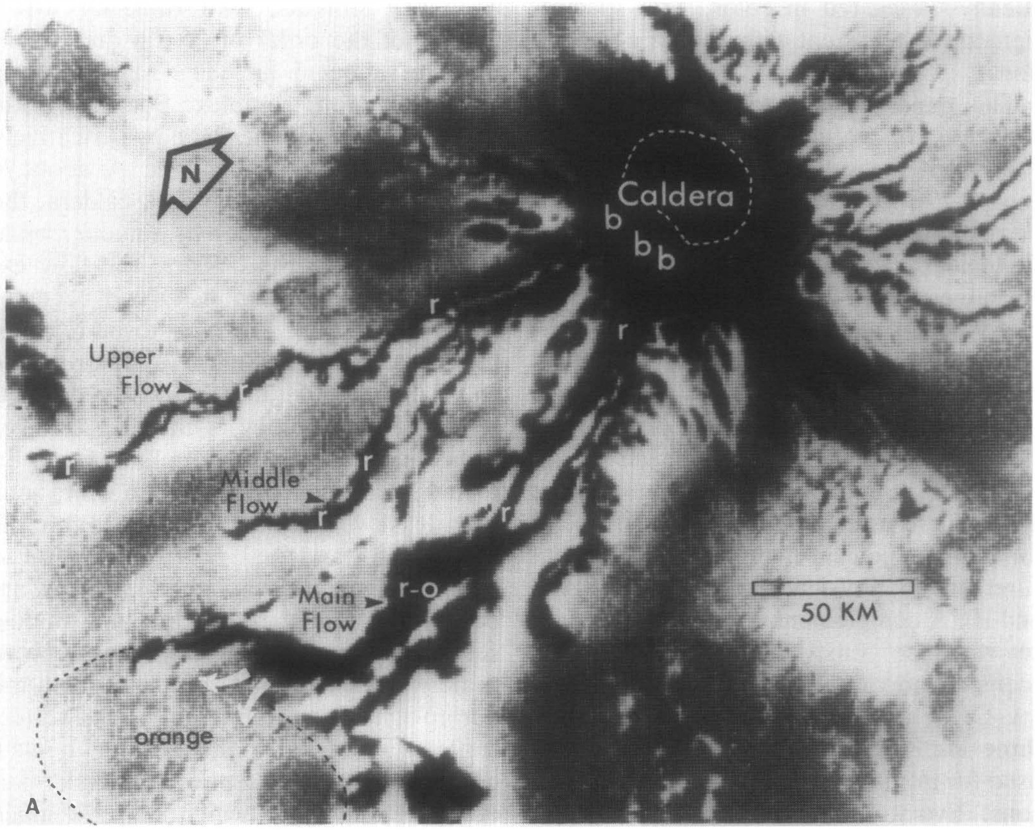

FIG. 2A. This is part of Voyager 1 close encounter image PICNO 041J1 + 000 showing the Ra Patera volcanic complex discussed in this paper. Three flows are labeled (Upper, Middle, and Main), as are rough indications of the qualitative colors of flow sections: b = black, r = red, r–o = red–orange. The large distal orange region is also delineated and labeled as the caldera region.

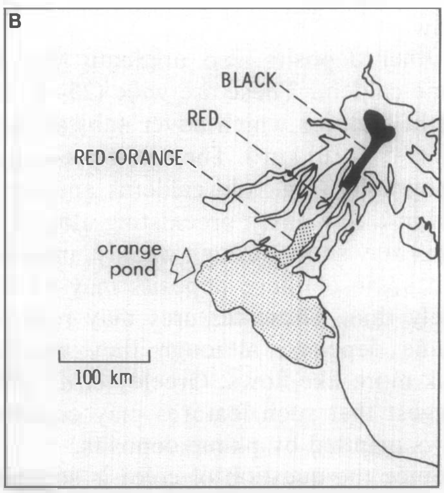

FIG. 2B. This is a sketch map of the main sulfur flow at Ra Patera. The qualitatively determined color zones are labeled.

dera by sampling their response in several bandpasses of Voyager high resolution image data. We found the violet, blue, and orange filters to be the most useful, because that suite represented the best balance of spectral range and contrast.

The central caldera and presumed source of the flows appears black at all wavelengths (<5% reflectivity). This is consistent with measurements of caldera features on Io by other investigators (Soderblom *et al.*, 1980; Clancy and Danielson, 1981). The albedo of the caldera is essentially uniform across its middle, but tends to brighten slightly toward its margins (10–20%) with an abrupt brightening at the boundary with the surrounding bright material.

The flows exhibit far more color variation than the caldera feature. Figures 3A–C are plots of the calibrated (Danielson *et al.*, 1981) zero-phase reflectivity in the Voyager narrow-angle broadband blue filter divided by the response in the orange filter for the darkest parts of the centers of the Main, Upper, and Middle Flows at Ra Patera, versus downflow distance. Data were taken from a series of transverse scans of several dozen points along the flows, from the caldera up to and including the flow fronts. Reflectivity ratio values were used here rather than absolute reflectivities because they are far less affected by systematic photometric errors (e.g., surface powder multiple scattering effects, addition of a uniformly bright component such as SO_2 frost or white sulfur, calibration errors; D. Nash, L. Soderblom, J. Veverka, J. Gradie—personal communications).

The generally lower albedo of the caldera region extends some 10 to 20 km into the centers of the most proximal reaches of both the Middle and Main Flows. In both cases, the flow interior, dark near the caldera, appears to systematically brighten and to exhibit a systematic increase in the blue/orange ratio in the downstream direction (Figs. 3A–C) as well as outward from the flow center in the direction transverse to the longitudinal flow axis. Progressive general brightening of flow centers and margins occurs down the lengths of all three flows which were examined, with one important exception. At the distal termination of the Main Flow, there appears to be an abrupt brightening and widening of the flow as already mentioned. The reflectivity of this area is about a factor of three higher than the darker upstream flow reaches, in all filters, and is particularly high in the orange filter. For purposes of discussion we term this zone the "Orange Pond." Previous sketch maps of the Orange Pond show it as a unit separate from the Main Flow (Strom *et al.*, 1979). More detailed scrutiny reveals, however, that (1) there is no discrete boundary or aura between the dark part of the Main Flow and the Orange Pond area (Baloga *et al.*, 1984), as is clearly present at many other contacts between the flow and the smooth bright adjacent material; (2) albedo features which cross between the dark part of the flow and the Orange Pond can be discerned; and (3) the Orange Pond is spectrally distinct from the smooth bright material which surrounds it. Thus, on the basis of morphology and color, we have mapped the Orange Pond as the distal continuation of the Main Flow. While it is true (A. McEwen, personal communication, 1983) that the flow fronts of several branches of the dark distal part of the Main Flow appear to onlap or abut the pond, at least two branches appear to merge with it.

In summary, we find the three flows which we examined to be spectrally distinct from the smooth bright material that surrounds them and to exhibit a continuous and systematic brightening and an increase in blue/orange reflectivity ratio downstream along their longitudinal flow axes. For reaches proximal to the caldera, we find essentially identical reflectivity values for both the caldera and the central parts of the adjacent flows. The distal reaches in two flows (Upper and Middle) contrast strongly with the surrounding material; however, in one case (Main Flow), we find a bright smooth distal termination with overall reflectivity only modestly distinct from the surrounding smooth bright plains material, yet apparently continuous in albedo and morphology with branches of the darker upstream section of the flow. In addition, along all three flows we find continuous brightening and a systematic increase in the ratio of the blue/orange filter reflectivities, when moving across a flow from its center to its margin.

INTERPRETATION

The question of whether sulfur lavas exist on Io is intriguing and has provoked much discussion (e.g., Nelson and Hapke, 1978; Sagan, 1979; Smith *et al.*, 1979; Carr and Clow, 1980; Schaber, 1980; Sinton,

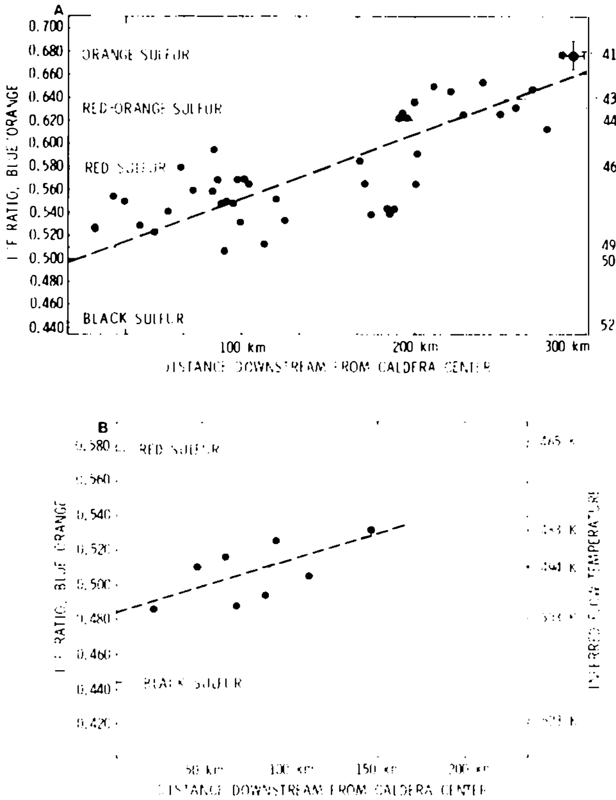

FIG. 3A. Shown here is a plot of the normalized reflectivity, I/F (Danielson *et al.*, 1981) in the blue and orange Voyager narrow angle camera filters versus downflow distance. White dots are individual data points taken from the ratios of decalibrated Voyager images. The data points were taken from scans transverse to the longitudinal flow axis at various distances from the center of the caldera region. The data points represent the transverse center of the flow as defined by reflectivity minima in the scans. A simple least-squares regression line (dashed) was fit to the data ($R = 0.82$, $N = 47$, $P < 0.001$). The point at the far right with range bars represents the location of the four data points which are nearly identical. (R is the correlation coefficient, N is the number of variates and P is the probability of the correlation coefficient being exceeded by a random population.) (B) This figure is a representation identical in technique and format to A for the Middle Flow at Ra Patera. The zero intercept of the best-fit line corresponds to an initial sulfur eruption temperature of 503°K. (C) Figure identical in technique and format to A and B for the Upper Flow at Ra Patera. The best-fit zero intercept corresponds to an eruption temperature of 497°K.

1980; Baloga *et al.*, 1981; Pieri *et al.*, 1981). While a definitive assessment of the validity of the sulfur flow hypothesis will require spacecraft and laboratory observations more detailed than those currently available, the morphological and color data already in hand seem clearly to support the hypothesis.

Color differentation between the caldera, the presumed source of the flows, and the flows themselves is pronounced. The observation of a low albedo zone, with an albedo identical to that of the caldera, extending down the middle of two of the flows is suggestive of an intimate association between the flows and the caldera and of ma-

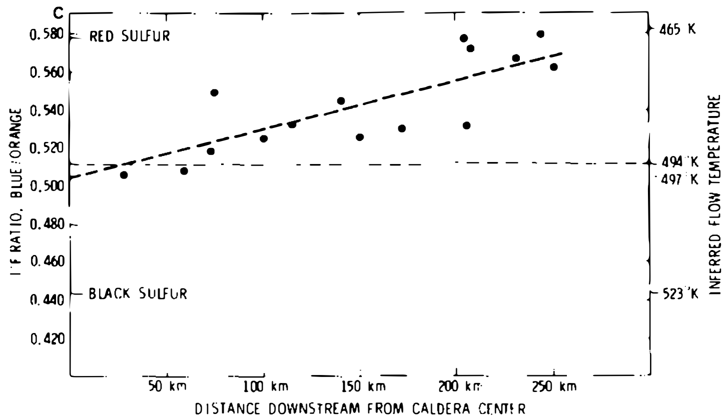

FIG. 3—*Continued.*

terial within the caldera having moved as part of the flow. Both observations are suggestive of the caldera being the source of the flows, but being photometrically differentiated from the flow material. The transition between the caldera interior and the flow suggests at least three possibilities: (1) that there is a surface textural transformation such as between aa and pahoehoe, (2) that the flow may have emerged from under a photometrically differentiated overlying crust as may be covering the caldera interior, or (3) that although the caldera and the associated flow are texturally and structurally similar, there has been a progressive colorimetric transformation of the flow front as it moved away from the source during its emplacement. While a textural transition cannot be completely ruled out, it is likely that a change in roughness will affect the apparent albedo in all three filters similarly, which is not observed. Rather, the color changes drastically. Emergence from beneath a crust cannot be ruled out. There is no sharp boundary at the resolution of the images (2 km/line pair), nor any indication of rafts of dark crust embedded in more distal portions of the flow. But a progressive colorimetric alteration is consistent with the observed color changes at the caldera–flow transition, as well as with observations of downstream reaches along all three of the measured flows.

The right ordinates of Figs. 3A–C are blue/orange reflectivity ratios. For the purpose of comparing the observed reflectivity ratios of the Ra Patera flows with the laboratory reflectivities of sulfur allotropes, we show zones centered on the blue/orange color ratios of black, red, and orange sulfur as would be seen by the Voyager cameras. The values used here for the allotropic reflectivity ratios are the ratios of laboratory reflectances as calculated by us from the published tabulation of Clancy and Danielson (1981), who convolved normal reflectance spectra measured in the laboratory (J. Gradie and J. Veverka, personal communication; Soderblom *et al.*, 1980) with the response functions of the Voyager camera filters and the solar spectrum (Clancy and Danielson, 1981). The left ordinate is a temperature scale in degrees Kelvin. We have calibrated this scale by taking the temperature characteristic of each liquid sulfur allotrope and assigning the laboratory-measured blue/orange ratio to that temperature. This procedure yields a deduced correspondence between temperature and color ratio. The data shown are the blue/orange reflectivity ratios of the darkest three pixels at the center of the flow at the longitudinal distance indicated on the abscissa. The pixels with the lowest violet reflectivity were designated as the "darkest" pixels.

Figures 3A–C are remarkable in several ways. First, the color data are highly correlated with distance. A systematic increase of reflectivity ratio with distance is clearly apparent for all three flows and the slope of the best-fit linear least-squares regression is similar for all three. Second, the range of reflectivity ratios of the flow centers of all three flows apparently falls in the range of reflectivity ratios measured in the laboratory for samples of black, red, and orange sulfur quenched from the liquid state. Third, the reflectivity ratios of all three flows for reaches nearest the caldera are in the range between that of orange and red sulfur allotropes, while two of the flows (Upper and Middle) terminate in the range of the red allotrope. The blue/orange reflectivity ratio for the Main Flow termination (Orange Pond area) falls between the ratios measured for the orange and red sulfur allotropes in the laboratory. Because of the strong relationship between distance and color and the implied relationship between distance and temperature, it is tempting to extrapolate the linear least-squares best-fit line back to its zero kilometer intercept in order to infer an initial sulfur eruption temperature. Such an extrapolation performed on each of the three data sets yields an initial eruption temperature of about 500°K in the range of the black sulfur allotrope.

The relationship between color and morphology in all three flows, particularly in the context of the visco-thermal properties of sulfur, deserves comment. Red sulfur is the most viscous allotrope of liquid sulfur, reaching a peak of 10^4 cP at about 465°K. Both the black and orange allotropes have viscosities lower by orders of magnitude, with black sulfur exhibiting a viscosity of about 100 cP at about 700°K (near boiling at 1 atm pressure) and orange, having the lowest viscosity of any sulfur allotrope, of around 10 cP at about 390°K. Reaches of all three flows emanating from the black caldera are relatively broad and, while slightly curved, are far less sinuous than more distal reaches. The parts of flows that have blue/orange ratios in the range of laboratory values for red sulfur appear to have the highest sinuosities and tend to be the narrowest parts of the flows. This effect is particularly pronounced along the Main Flow. The Upper and Middle Flows, both being narrow and sinuous monofilaments, have Voyager blue/orange ratios in the range of red sulfur. The Main Flow exhibits a more sinuous character in this same range of blue/orange ratios, but as that color ratio increases toward values between red and orange sulfur, the flow begins to widen and branch. Eventually in its most distal reach, the Main Flow widens considerably and takes on values in the range of orange sulfur. If the Main Flow were composed primarily of sulfur, as the overall flow temperature dropped into the range of the low viscosity orange allotrope, a major change in flow character could then have rapidly occurred, particularly because of the steep dependence of viscosity on temperature in the narrow range of 444 to 434°K. If the flow viscosity catastrophically drops with cooling, the flow should thin, spread out, and increase in velocity, changing rapidly from a relatively narrow and directed flow into a broad thin sheet. Taken together the systematic and color progressions from the caldera downstream through the transition into the Orange Pond are consistent with a mainly sulfur composition.

In the context of observations of central vent volcanoes elsewhere in the solar system, the morphology of the Ra Patera complex is unremarkable, beyond the fact that Ra flows appear voluminous compared to most flows on Earth. Much of the variation in morphology could be attributed to topographic variability, and the assumption that the flows at Ra Patera are composed purely of silicates would not be questioned on these morphological grounds any more than that assumption is generally questioned for volcanic structures on Mars. It is the existence of systematic sulfur-like color parameter progressions within the flows which give meaning to similarly systematic, but otherwise unremarkable, morphological variations. Taken together in the global geochemical context of Io, these observations make the sulfur lava hypothesis a credible alternative to the assumption of silicate volcanism. No claim has been made that these color/morphology correlations can be understood by pure silicate, or any other variety of even hypothetical nonsulfur volcanism.

FLOW THERMAL DYNAMIC MODEL AND INTERPRETATION

Since we have found the progression of color and morphology within the flows at Ra Patera to be consistent with sulfur lava, it is natural to investigate whether the physical chemistry of sulfur allows sulfur lava flows with the dimensions of the Ra Patera flows.

The rate at which a lava flow loses heat and the mode in which that heat loss occurs, along with composition, are fundamental intrinsic influences on the morphology of the flow. If we assume radiative cooling and flow composition, and measure the temperature of two known points along the flow, as well as flow width, we can then calculate an effusion rate. Sulfur lava may provide a unique opportunity in this regard. If colors characteristic of flow temperatures at a given distance from the source are preserved in the flow as it cools, a colorimetric geothermometer may exist. In addition, because of the drastic viscosity changes over a small temperature range, flow morphology may be highly dependent on temperature for sulfur lavas. Using color and morphology, we can in principle estimate flow temperature as a function of distance from the source and employ a heat loss model to calculate independently an initial eruption temperature for the Ionian flows, to be

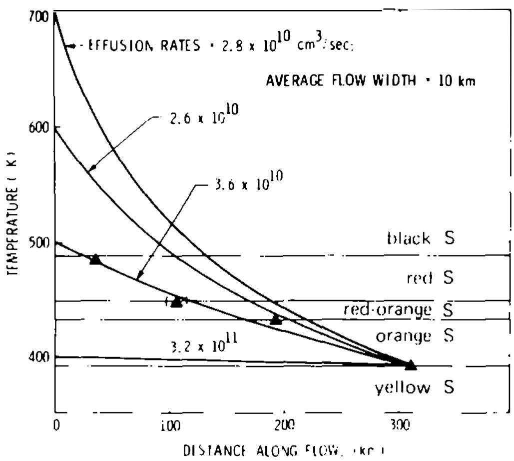

FIG. 4. This is a graph of predicted temperatures along the Main Flow at Ra Patera, assuming that nearly all heat is lost through radiation, for a range of assumed initial eruption temperatures. Also indicated are data points (triangles) determined by qualitative evaluation of the colors and morphology. Several independent lines of data (see text) are consistent with an initial temperature of about 500°K. The effusion rates listed are calculated using the radiative cooling model (see Eq. (4)) and are unique to the choice of initial temperatures and width.

compared with the "zero-intercept" temperature estimate from the colorimetry alone (Fig. 4).

To model heat loss in the flow, we use a simple one-dimensional heat transport equation (Pieri and Baloga, 1984),

$$\rho c_p \left(\frac{\partial}{\partial t} + \bar{u}\,\frac{\partial}{\partial x}\right) TYW = -\varepsilon\sigma T^4 W \quad (1)$$

where $T = T(x,t)$, $W = W(x)$, and $Y = Y(x)$ denote respectively the flow temperature, width, and depth for constant effusion rate Q and mean flow velocity $\bar{u}$, where $Q = \bar{u}WY$, ρ is the density, c_p is the specific heat capacity at constant pressure, ε is the emissivity, σ is the Stefan–Boltzmann radiation constant, t is time, and x is the distance down the flow. Equation (1) represents energy transport by the flow with heat loss due to radiation and allows for changes in geometry along the flow path.

Since the flow width and its variation are measurable, then for a given source temperature dependence on time, $T_0(t)$ at $x = 0$, Eq. (1) has the solution

$$T(x,t) = \left\{ T_0^{-3}[t - (x/\bar{u})] + (3\varepsilon\sigma/\rho c_p Q) \int_0^x W(y)dy \right\}^{-1/3} \quad (2)$$

with T_0 (the eruption temperature) and Q to be inferred from analysis of the data. Notice that the time dependence of the solution appears solely in the boundary value function, $T_0[t - (x/\bar{u})]$. For a constant source temperature, our solution becomes stationary in time, and from (2) we arrive at

$$T_0 = T_2\{1 - [1 - (x_1/x_2)]^{-1} \cdot [1 - (T_2/T_1)]\}^{-1/3} \quad (3)$$

and

$$Q = [3\varepsilon\sigma(x_2 - x_1)\overline{W}_{12}] / [\rho c_p(T_2^{-3} - T_1^{-3})], \quad (4)$$

yielding an initial temperature, T_0, and an effusion rate, Q, from the estimation of the temperature (T_1 and T_2) at any two points (x_1 and x_2) along the flow, for a mean flow width of $\overline{W}_{12}$, between points x_1 and x_2.

To estimate flow temperature as a function of distance down the flow, we used two methods: (1) qualitative estimation of where the transition occurs between successive allotropic regimes on the basis of photogeologic interpretation, and (2) quantitative estimation using the reflectivity ratios of the transitions as shown in Figs. 3A–C. In working from Voyager images we identified basic morphological and albedo styles within the flows and assumed that each could be associated with a sulfur allotrope regime.

Using the first technique, reaches identified as "black" are the flow segments emanating from the caldera with the albedo characteristic of the caldera interior; they tend to have smoothly curving margins, and are interpreted here as having a predominantly black sulfur composition. "Red" reaches are narrow and sinuous with crenulated margins, appearing qualitatively lighter than adjacent upstream reaches in all filters but with flow centers distinctly darker than flow margins, and are interpreted here as being predominately composed of red sulfur. The "orange" designation is used only for the Orange Pond feature at the distal end of the Main Flow. It appears much brighter than the other two zones, has smooth curvilinear flow margins with approximately uniform albedo, and is interpreted here as being mainly orange sulfur. The temperatures of the transitions between sulfur allotrope colors as measured in the laboratory were then assigned to the distances at which our inferred transitions occurred. The second technique is more straightforward. Here, from Figs. 3A–C, temperatures were determined from the value of the least-squares regression line at the downflow distances determined by technique (1).

TABLE IIA

TABULATION OF DATA AND MODEL VALUES FOR DOWNFLOW DISTANCE AND INFERRED TEMPERATURE

Data		Models	
Downflow distance (km)	Inferred from morphology and qualitative color	Thermal model without distal expansion	Thermal model with expansion included
25	494 K	493 K	474 K
109	444 K	453 K	443 K
193	434 K	423 K	418 K
313	392 K	392 K	392 K
Downflow distance (km)	Inferred from color ratio graph	Thermal model without distal expansion	Thermal model with expansion included
0	501 K	514 K	509 K
109	478 K	455 K	453 K
193	468 K	425 K	424 K
313	392 K	392 K	392 K

The results of applying these techniques is shown in Tables IIA and B and in Fig. 4. Table IIA presents a comparison of the results of these two techniques for the Main Flow and also a set of calculated downflow temperatures resulting from the best fit of a theoretical thermal profile generated by Eq. (3) to those data values. We have calculated the theoretical temperatures both for an average flow width and for a linear downflow

TABLE IIB

COMPARISON OF INITIAL ERUPTION TEMPERATURES AND EFFUSION RATES FOR FLOWS AT RA PATERA CALCULATED USING DIFFERENT METHODS

Flow name	Best fit to thermal model: Calculated from qualitatively-based distance estimates	Best fit to thermal model: Calculated from reflectivity ratio-based distance estimates	Calculated from zero-intercept value of reflectivity ratio
Main			
T_0	485 ± 26°K[a]	509 ± 21°K[a]	501°K
	508 ± 36°K	514 ± 21°K	
Q	$7 \pm 3 \times 10^{10}$ cm³/sec[a]	$9 \pm 4 \times 10^{10}$ cm³/sec[a]	4×10^{10} cm/sec
	$5 \pm 3 \times 10^{10}$ cm³/sec	$7 \pm 5 \times 10^{10}$ cm³/sec	
Upper			
T_0	508°K	496°K	497°K
Q	1×10^{11} cm³/sec	2.5×10^{11} cm³/sec	2.5×10^{11} cm³/sec
Middle			
T_0	517°K	507°K	503°K
Q	1×10^{11} cm³/sec	1.5×10^{11} cm³/sec	1×10^{11} cm³/sec

[a] Values calculated allowing linear distal flow expansion.

expansion in the lower part of the flow which more accurately models the observed Main Flow. Figure 4 graphically shows the data points generated by our qualitative method (Technique 1) as compared to model thermal profiles from Eq. (3). Table IIB shows best-fit eruption temperatures and effusion rates calculated by fitting Eqs. (3) and (4) to the downflow allotropic transition distances for all three flows determined using qualitative (Technique 1) and quantitative (Technique 2) criteria. Also listed are the eruption temperatures determined by the zero-intercept extrapolation from the regressions shown in Figs. 3A–C.

Tables IIA and B and Fig. 4 have several implications. For each flow, the three methods independently estimate the same mean eruption temperatures, with a variance of about 25°. The first two methods (Table IIB, columns 1 and 2) are based on a fit to our radiative cooling model, but the determination of the temperatures that generate the fit is done in different ways—one by inferring temperature on the basis of morphological/qualitative-color changes downflow and the other by inferring temperature from color ratios measured in the laboratory. The third method (Table IIB, column 3) is a purely empirical fit.

Effusion rates calculated using Eq. (4) are comparable to the peak effusion rates of the largest terrestrial basaltic eruptions (Table III), and thus are not geologically unreasonable, particularly since the low melting point and heat of fusion of sulfur favors a high effusion rate when compared to basalt for a given available eruption energy (O'Reilly and Davies, 1981). Figure 4 shows that the inferred cooling rate as a function of distance is not unreasonable for a radiatively cooled lava flow of sulfur composition. Because values generated by all three methods agree, and because reflectivity ratios by themselves suggest a sequence of sulfur allotropes, the contention that the Ra Patera flows are radiatively cooled sulfur lavas is tenable.

The steep decrease in viscosity of sulfur in the range 444 to 433°K suggests that the kinematic behavior of a sulfur lava may be

TABLE IIC

CALCULATIONS OF FLOW PARAMETERS FOR THE MAIN FLOW AT RA PATERA FOR HIGH VISCOSITY (HV, E.G., BLACK AND RED SULFUR ~10^4 CP) AND LOW VISCOSITY (LV, E.G., ORANGE SULFUR, ~10 CP) ALLOTROPE SEGMENTS FOR A CALCULATED EFFUSION RATE (~6×10^{10} cm^3/sec)[a]

Flow depth (m)		Mean flow velocity (cm/sec)		Flow time within segment (days)		Total duration of flow (days)	Total flow volume (cm^3)	Total energy (ergs)
HV	LV	HV	LV	HV	LV			
25	1	23	79	9	2	11	5×10^{16}	5×10^{26}
100	5	6	20	38	7	45	2×10^{17}	2×10^{27}
250	14	2	8	96	17	113	5×10^{17}	5×10^{27}

[a] Flow parameters here were calculated for various HV flow depths, using Eqs. (5) and (6) for the planimetric dimensions of the Main Flow. The total energy content was calculated under the Williams and McBirney (1979) definition of $c_p T_0 V$ as defined in the text.

radically different from that of basalt. At the 434°K transition between the high viscosity (>10^3 cP) and low viscosity (<10^3 cP) segments of the flow, the viscosity decrease could cause a flow velocity gradient until approximately steady kinematic conditions are again established downstream. To appreciate the significance of this viscosity-induced transition, suppose both high and low viscosity steady flows are laminar. The flow depths and mean velocities in each region are related by

$$y_h/y_l = [w_l \nu_h / w_h \nu_l]^{1/3} \tag{5}$$

and

$$u_h/u_l = [w_l/w_h]^{2/3}[\nu_l/\nu_h]^{1/3}, \tag{6}$$

where y_h and y_l are the thicknesses of the proximal (high viscosity) and distal (low viscosity) portions of the flow, w_h and w_l are the widths, ν_h and ν_l are the viscosities, and u_h and u_l are the mean flow velocities, all for a constant slope and effusion rate. The observed flow widths for the Ra Patera Main Flow (w_l ≈ 50 km, w_h ~ 10 km) imply a thinning of the orange flow relative to the red flow by a factor of about 25 with a factor of about 3 velocity increase (Table IIC). Such a transition, of course, is dramatically different from the behavior of silicate lavas.

At the distal end of the Main Flow, we have interpreted the Orange Pond to be composed of orange sulfur (Fig. 2B). Multiple sources for the Pond may exist at the transition zone, since the red reach of the Main Flow divides near there into smaller parallel flows. The outlined perimeter of the Pond probably represents the termination of transverse expansion, rather than the outline of the flow path. The smooth, featureless, bland appearance of the Pond suggests free-flow expansion, characteristic of Newtonian fluid behavior. It is possible that after the orange flow front solidified, lateral expansion continued to occur in parts of the flow nearer to the caldera.

Using Eqs. (1), (2), and (6), we can also calculate the flow duration and an energy

TABLE III

COMPARISON OF SELECTED PEAK VOLCANIC EFFUSION RATES ON THE EARTH AND IO[a]

Volcano name	Lava type	Effusion rate	Date
Hekla, Iceland	Basalt	2.8×10^{10} cm^3/sec	1947
Mauna Loa, Hawaii	Basalt	2×10^{10}	1887
Paracutin, Mexico	Basalt	6×10^{6}	1945–1946
Sakurajima, Japan	Andesite	2×10^{9}	1914
Santorini Dome, Greece	Dacite	5×10^{5}	1966
Ra Patera, Io	Sulfur	10^{10}–10^{11}	1979

[a] Terrestrial values adapted from Williams and McBirney (1979).

TABLE IV

THERMAL ENERGY CONTAINED IN ERUPTION PRODUCTS FOR SOME SELECTED TERRESTRIAL AND IONIAN VOLCANIC ERUPTIONS[a]

Volcano	Year	Total energy (ergs)	Eruption type
Tambora	1815	8.4×10^{26}	Explosive
Kusatsu–Shirane	1932	1.6×10^{18}	Explosive
Iceland	Entire postglacial	10^{28}	Flow
Parcutin	1945–1946	5×10^{25}	Cinder/flow
Etna	1669–1865	1.5×10^{26}	Flow
Ra Patera, Io	1979	$\sim 10^{26}$	Flow (sulfur)

[a] Terrestrial values adapted from Williams and McBirney (1979).

content, defined as c_pT_0V, where V is the total flow volume (Williams and McBirney, 1979), as shown in Table IIC. The Main Flow has an energy content of about 10^{26} ergs, if we assume a depth of about 1 m for the Orange Pond, implying a depth of about 25 m at the caldera. The energy content of several terrestrial volcanic eruptions are listed in Table IV. The Main Flow at Ra Patera is similar in energy content to that of a large terrestrial basalt construct. While 10^{26} ergs may seem high for one flow on Io, the Ionian heat flux (Matson *et al.*, 1981) is about 30 times the terrestrial value and about 100 times that of the Moon. The heat loss rate of the Main Flow is about 10% of the average of Io. Such flows are of low intensity and cool slowly as opposed to the intense short-lived "5 micron bursts" (Fink *et al.*, 1978; Witteborn *et al.*, 1979; Sinton, 1980; Pearl and Sinton, 1981).

The effusion rate calculated here can also be used to determine a global resurfacing rate if certain assumptions are made. If we use the computed effusion rate from a Ra Patera-like volcano with at least one flow like the Main Flow active at all times on Io, we can calculate the time necessary to resurface Io to a depth of 1 km. This is the characteristic depth of burial which must occur to obliterate 5-km-diameter and larger impact craters (Johnson *et al.*, 1979). We find the characteristic timescale for resurfacing of Io by flow volcanism, given our modest assumptions as to flow geometry, to be about 10^5 years. That is, Io would be buried to a depth of about 1 km in about 100,000 years, at a rate of about 1 cm per year. This rate is in excess of the rate calculated for Ionian plumes by Johnson *et al.* (1979) by three to four orders of magnitude. Our range of assumed effusion temperatures and rates are illustrated in Fig. 5.

The resurfacing rate calculated here is also consistent with resurfacing rates based on geochemical considerations offered by Lewis (1982). He calculates a theoretical eruptive mass flux maximum corresponding to the addition to the surface of 15 cm per year, based on the heat capacity of liquid sulfur and the estimated available energy. Lewis also points out that on Earth up to 400 km^3 of lava effusion would be necessary for convective transport of the internal heat dissipated through the crust each year. In

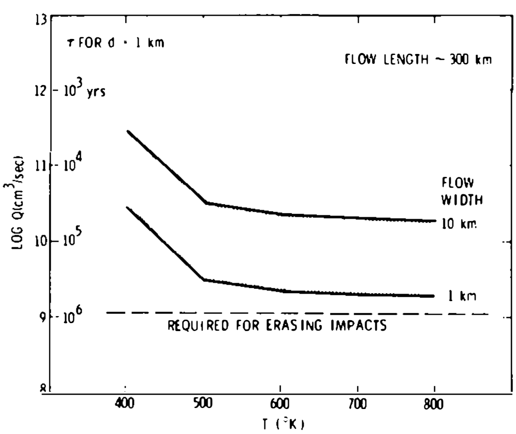

FIG. 5. Effusion rate (Q) calculated from our radiative cooling model for sulfur lava is shown plotted against initial flow eruption temperature (T) for the Main Flow at Ra Patera for the range of flow widths shown here in stipple. The flow length in this case is assumed to be 300 km, roughly the length of the Main Flow. Assuming only one flow like the Main Flow active at any given time on Io, we derive τ = the time necessary for global resurfacing to the depth d = 1 km, which is the estimated depth of cover needed to erase craters 5 km in diameter and larger (Johnson *et al.*, 1979). The minimum resurfacing rate needed (Johnson *et al.*, 1979) to erase craters in that size range is indicated by the dashed line.

reality, only about 6 km^3 of lava is actually extruded every year, mostly along mid-oceanic ridge systems. While our estimated value of about 1 cm per year due to sulfur lava flows on Io implies that proportionally more heat is lost through extrusion on Io than on Earth, given the higher heat flow, abundant evidence for continuing volcanic activity, and a higher relative extrusion rate for Io, our result seems plausible.

DISCUSSION

The major area of uncertainty in the study of sulfur lavas on Io is the mechanism of color preservation. In terrestrial sulfur flows, colorful high temperature allotropes revert to lower temperature allotropes as they cool to ambient temperatures (~290°K). The original appearance of observed flows changes markedly over the period of a few hours (Watanabe, 1939). On the other hand, colors of small quantities of pure high temperature sulfur allotropes, when rapidly quenched, have been preserved indefinitely in laboratory experiments (Meyer, 1976, and private communication; see also Sagan, 1979). Here we have presented evidence of retention of colors characteristic of sulfur allotropes in the flows at Ra Patera (Figs. 3A–C). The detailed mechanism by which this color retention is effected in sulfur flows on Io is a matter of current debate (Nelson *et al.*, 1983; Fink *et al.*, 1983; also, A. T. Young, J. Gradie and D. Matson, private communications). Nevertheless, the agreement between the initial temperatures calculated using the radiative cooling model and the initial temperatures determined from both quantitative and qualitative analysis of color and morphology argues that the appearance of the flows is characteristic of their heat content. Specific mechanisms to facilitate color retention, however, remain problematical and must await further laboratory and theoretical work.

Besides the Main, Upper, and Middle Flows, there are other flows at Ra Patera of a different morphology that may be more important with regard to resurfacing. These flows are broad and diffuse and we attribute them to the direct eruption of low viscosity orange sulfur. In looking at the global distribution of such flow morphologies, we estimate that the broad diffuse flows occupy between one and two orders of magnitude more surface area than the well-defined sinuous flows, such as the Main Flow at Ra Patera. Moreover, if we interpret other less well-defined broad smooth orange sheets as being the result of fissure eruptions of orange sulfur, then another several orders of magnitude of surface area can be added to the broad flow category.

The rheological properties of sulfur with respect to temperature (Fig. 1) inherently suggest a diverse suite of potential sulfur flow morphologies. Over a range of 60°K the anticipated sulfur flow morphologies vary from broad, highly reflective orange flows of low viscosity to narrow, low albedo black or red highly viscous flows. At some points on the sulfur viscosity–temperature curve, gradients as high as 10^3cP/°K exist. While the presence of silicate volcanism is by no means excluded, volcanic flows on Io exhibit a wide range of morphology and color (Schaber, 1980) consistent with rapidly changing physical properties and thus with the sulfur lava hypothesis. Strong morphological and color gradations can be seen not only between flows but within a single flow (e.g., Main Flow, Ra Patera). In contrast, silicate flows have a far weaker viscosity–temperature dependence, and the physical nature of the temperature–viscosity relationship of silicate (Williams and McBirney, 1979) is radically different. Gross morphology for silicate lava flows is less sensitive to temperatures than to other parameters such as overall volatile and silica content and effusion rate (Pinkerton and Sparks, 1976), yielding a less diverse morphological spectrum than sulfur lava for a given temperature differential.

While silicate lavas are rarely superheated, the observation of local occurrences of higher temperature sulfur allotropes at the surface may be evidence that sulfur lavas on Io are heated above their local melting points at depth. When crustal sulfur is heated into its most mobile allotrope, it may move upward along conduits of opportunity producing the broad orange flows that predominate on Io. However, if sulfur is superheated by local subcrustal heat sources—perhaps by silicate intrusions—a rapid evolution of higher temperature allotropes could occur, resulting in the creation at the surface of calderas and the extrusion of red or black sinuous flows, and perhaps, in some cases of extreme temperature contrast, plume eruptions.

CONCLUSION

We have examined the morphological and colorimetric properties of flows of the Ra Patera complex using several methods of analysis designed to be as simple and independent as possible. We have found the suite of observed morphological and colorimetric characteristics to be consistent with sulfur lava that has cooled predominately by thermal radiation.

Calculated effusion rates and energy content are roughly equivalent to those observed for large terrestrial basalt eruptions. The global resurfacing rate for sulfur lavas inferred from this study is of the order of 1 cm per year, which is consistent with calculations of available energy globally. Calculated emplacement timescales for the Ra Patera flows vary from weeks to a few months, depending on flow depth assumed. There is no evidence that the flows at Ra Patera were active during the Voyager observations, since liquid sulfur if exposed would appear black (Nelson *et al.*, 1984), although that possibility cannot be precluded elsewhere on Io. Subsequent work on Ionian volcanism should involve better characterization of different types of flow morphologies, detailed color analysis of the flows, and the study of the relationships between volcanic flows and other features, such as auras (Baloga *et al.*, 1984) and plumes.

ACKNOWLEDGMENTS

This research was supported under NASA Contract NAS 7-100 at the Jet Propulsion Laboratory and by NASA Grant NGR-33-010-220 to Cornell University. Baloga was supported as a NASA–National Research Council Senior Research Associate at JPL during part of the duration of this work. We thank J. Gradie, A. Gillespie, E. Ivins, D. Matson, L. Soderblom, R. S. Saunders, and J. Veverka for helpful discussions, and, in particular, D. Nash, A. Young, J. Fink, A. McEwen, and G. Schaber for thorough and helpful reviews. We particularly thank S. Wall for his unselfish assistance with image processing.

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