1990LPICo.740...22K

MODELS OF SOLAR-POWERED GEYSERS ON TRITON;

R. L. Kirk, U.S. Geological Survey, Flagstaff, AZ 86001

Introduction A highlight of the Voyager 2 encounter with the Neptune system was the discovery by Laurence Soderblom of the U.S. Geological Survey of actively erupting geyser-like plumes on Triton. A series of images from different viewing angles obtained as the spacecraft flew past Triton clearly shows at least two plumes above the satellite's surface. The plumes, which appeared dark relative to the surface beneath them, included a vertical column that rose to an altitude of about 8 km (5 mi), and a subhorizontal dark cloud that extended westward for several hundred kilometers. Other images revealed long, east-west clouds recognized as bright features over Triton's night side that were similar in form to the clouds attached to the eruption columns. Localized bright clouds were seen silhouetted over the day-side horizon in yet other images. These clouds may all be manifestations of the same eruptive phenomenon. Both the plumes and the clouds were located within the area of the south polar cap, at latitudes ranging from 30° to 60°S. This localization, combined with the fact that the current latitude at which the sun passes overhead is 45°S, suggests the eruptions are powered (or at least in some way triggered) by sunlight. I have been modeling solar-powered Triton geysers, seeking to understand (1) the processes that might be involved in channeling solar energy to an erupting geyser, (2) the size and properties of the subsurface region from which the eruptive fluids might be derived, and ultimately (3) whether solar energy could account for the observed eruptions on Triton.

Properties of the Geysers The possibility of currently active eruptions had been raised by Soderblom and other members of the Voyager Imaging Team earlier in the encounter with Triton, in an attempt to explain the many northeast-trending dark streaks seen on Triton's south polar cap. These streaks were found in the same range of latitudes where the active plumes were later discovered. The streaks strongly resembled dust streaks created by wind action on Mars, yet Voyager 2 measured the pressure in Triton's nitrogen atmosphere to be scarcely one one-thousandth the pressure of the Martian atmosphere. Soderblom and others suggested that gas erupted at a higher local pressure could carry dark particles that would be deposited downwind as a streak. The eruptive activity was thought to be very recent—to have occurred less than a few Tritonian years ago (each such year equals 165 Earth years). Otherwise the streaks would have been buried by nitrogen frost that condenses out of the atmosphere during the winter. It seems likely that the plumes later found are indeed related to the surface streaks. If so, we can use the relative numbers observed—roughly 10 plumes and clouds compared with perhaps 100 streaks—to estimate the length of time when any given plume is active: about one-tenth of the Tritonian summer, or 5 to 10 Earth years. The difference in trend between the plumes and streaks does not rule out their being related. A model of Triton's atmosphere by Andrew Ingersoll of Caltech predicted that the wind direction changes from northeast to west with increasing altitude. The plumes observed in action apparently reach the uppermost, westward-blowing layer of the atmosphere. Streaks that extend northeast from dark spots (presumed to be sources of vent areas) may be formed by less energetic eruptions that reached only the northeast-blowing atmospheric layer.

It is possible to estimate the amount of material being erupted. Both the horizontal parts of the plumes and their shadows appear about 5% darker than the surrounding surface. This suggests the suspended dust is nearly black and is abundant enough to intercept 5% of the light passing through the plume. Combining this observation with an estimate of the size of the dust particles (they must be big enough to absorb light efficiently, but not so big that they settle out of the plume), the radius of the plume, and the wind velocity from Ingersoll's model, Soderblom has calculated that about 1 kg (2 lb) of dust must be erupted per second. The amount of gas erupted is harder to estimate directly, but it might be roughly 20 times the amount of dust.

Susan Kieffer of the U.S. Geological Survey applied a fluid-dynamic model, developed to describe the eruption of terrestrial geysers and volcanoes, to the plumes on Triton. She found that the height of the Tritonian plumes could be accounted for if they were about 100 m (330 ft) across at the base, and if the erupted nitrogen gas were at a temperature of roughly 41 K (−386°F) before it expands and cools to the ambient temperature of 37 K (−393°F). Eugene Shoemaker, also of the U.S. Geological Survey, has pointed out that the geyser source to which the 100-m size applies is more likely on geological grounds to be a region of many closely spaced fissures or vents rather than a single large opening. If the height of the plumes is limited by a stratified layer in the atmosphere, a larger source diameter would be consistent with the observations.

TRITON GEYSER MODELS: R. L. Kirk

A Greenhouse on Triton A partial model of a solar-powered Tritonian geyser was described in the 30-day report of the Voyager Imaging Team [Smith, B.A., *et al.* 1989, *Science*, 246, 1422–1429]. In this model, solar energy is absorbed by dark material underlying a transparent surface layer of nitrogen ice. The low thermal conductivity of the nitrogen leads to a strong "greenhouse effect": the temperature, and hence the equilibrium vapor pressure of nitrogen, are greater below the layer than at the surface. If the nitrogen layer forms a gas-tight seal (it was suggested), a reservoir of pressurized gas might be built up in pore spaces below the surface. Rupturing of the seal, or lateral migration of the gas to regions where the seal is imperfect, would lead to venting of the trapped gas that might account for the observed eruptions.

Preliminary calculations by Robert Brown, Jet Propulsion Laboratory, and others indicate that the greenhouse mechanism could generate the required temperature increase. The intensity of sunlight at Triton is only one one-thousandth of that at the Earth, or about 1.5 watts per square meter; averaged over one Triton day, the power incident on an area near the subsolar latitude is roughly half as great. If this power were deposited at the base of a 2-m thick nitrogen layer and all of it were conducted upward, the temperature at the base would be 7.5 K higher than that at the surface. The temperature enhancement would be less if (as is likely) some of the sunlight were reflected, or if a significant amount of heat were conducted away from the greenhouse downward or horizontally.

Even if the greenhouse were perfect, so that all of the solar energy incident on it could be used to vaporize nitrogen to feed the geyser, a region 1.5 km (about 1 mi) in radius would be required to collect enough energy. If the loss of energy by conduction through the greenhouse layer is allowed for, the required radius increases to 4 km, or almost 100 times the inferred radius of the geyser source regions. Thus, for the insolation-driven geyser to work, energy must be transmitted to the geyser source region from a much larger surrounding "collector." This energy must be transmitted by a means that is much more efficient than thermal conduction in solid nitrogen; otherwise, conduction across the greenhouse layer would "short circuit" the geyser.

Energy-Transport Processes My investigations have indicated that, although the thermal conductivity of water ice is roughly 100 times greater than that of solid nitrogen, conduction in a water-ice layer could not transport the energy required for a Tritonian geyser. A much more promising means of energy transport is the flow of gas through pore spaces in the material below the greenhouse layer. Consider a localized region of the subsurface that is warmer than its surroundings. The gas pressure and density in the pores in this region will be enhanced in keeping with the equilibrium vapor pressure of solid nitrogen as a function of temperature. The pressure difference between the warm region and its surroundings will drive a flow of gas through the interconnecting pore spaces; in order to maintain the equilibrium pressure distribution despite this flow, nitrogen will evaporate in the warm region and condense where it is colder. Energy, in the form of latent heat, will consequently be transferred from one region to the other. This energy transport is in the same direction as ordinary thermal conduction, and one can define an "effective thermal conductivity" that describes the energy flow for a given temperature gradient. Unlike the ordinary thermal conductivity, however, the effective conductivity increases dramatically with temperature because of the strong temperature dependence of the vapor pressure and density. The mechanism of heat transport just described is the same as that employed in "heat pipes," hollow tubes containing a wick and a volatile liquid in equilibrium with its vapor, which are variously used for such purposes as controlling the temperature of spacecraft and baking potatoes more efficiently.

In addition to intrinsic properties of the gas, such as vapor pressure, latent heat, and viscosity (which determines the rate of flow under a given pressure gradient), the effective thermal conductivity depends on the permeability of the porous medium. The permeability is a measure of the ease with which fluid can pass through the pores; it is a function of the fraction of the total volume the pores occupy and of their size. I used a theoretical model relating permeability to porosity and to the size of the solid grains or blocks (on which the size of the pores depends) to calculate the effective conductivity of a porous nitrogen layer on Triton. To obtain reasonable success with the thermal models described below, I found it necessary to assume quite large grain sizes. For example, the numerical results I give here are for a grain size of 2 m (about 6.6 ft) and a porosity of 10%. The corresponding effective conductivity at the subsurface temperature of 41 K is about 4000 times the conductivity of non-porous nitrogen at the same temperature and roughly twice that of copper at room temperature.

The permeability required to achieve this effective conductivity is very large compared with reported permeabilities of terrestrial rocks and sediments, but this may be a matter of observational bias. Deposits of meter-sized boulders exist on Earth, but such deposits are so permeable that they are of little hydrologic importance, and their permeability is unlikely to have been measured; there is no real reason to suspect it is not as large as theory predicts. There is, moreover, a mechanism that might maintain a very porous and coarse layer of nitrogen on Triton's surface. The global equilibrium temperature of 37 K is only slightly above the temperature of 35.6 K (−395.6°F) at which solid nitrogen undergoes a phase transition. The lower-temperature phase is about 10% denser than the higher-temperature phase. Thus, if the temperature dropped only a few degrees below the equilibrium value during the winter, the solid nitrogen would contract and fracture, yielding roughly the 10% porosity assumed here. The fracture spacing (or block size) might well be comparable with the thickness of the nitrogen layer, making meter-sized blocks plausible for a layer several meters thick. Jostling of the blocks as they separated would ensure that the fractures would not reclose entirely when the temperature increased and the nitrogen converted back to the less dense phase.

Steady-State Thermal Models To understand the required geometry and size of a solar-powered geyser, I have calculated numerical models of the temperature field beneath the collector and geyser. I started with steady-state models, for several reasons. Steady-state models are simpler and faster to calculate than time-dependent ones, particularly for the temperature-dependent effective conductivity we are interested in. It is also possible to "scale up" the results of a single steady-state calculation to determine the temperatures in systems of different sizes; this is much less convenient for time-dependent models. Finally, steady-state models are realistic representations of two possible situations on Triton: a "reservoir" of gas and energy that has been created by the Sun but has not yet been tapped by a geyser, and a subsurface conduit that is receiving energy and passing it on to a geyser at an equilibrium rate. The geometry of my models is idealized: the collector is represented by a circular patch on the surface that supplies energy, and the geyser (if any) by a smaller concentric circle in which energy is extracted.

I also make an approximation of the method by which the greenhouse collector feeds energy into the subsurface region. In reality, a fixed amount of solar energy is absorbed at the base of the greenhouse, and the temperature adjusts itself so that thermal conduction upward to the surface and gas-phase transport downward together remove just this much energy, maintaining equilibrium. It is easier, however, to model two limiting cases of this behavior: (1) for a small collector, most of the energy is transported away by the gas rather than through the greenhouse, making it appropriate to specify the energy input into the subsurface; and (2) for a large collector, most of the energy is lost by conduction to the surface, making it appropriate to specify the temperature at the base of the greenhouse layer. Thus, in reality, the reservoir temperature achieved increases with size for small collectors, then levels out at a value controlled by the efficiency of the greenhouse layer. By comparing the two types of simplified models, I can estimate the size of the smallest collector that can approach the limiting temperature of the reservoir.

I assuming the effective conductivity described above and an energy input into the subsurface of $0.1\,\mathrm{W\,m^2}$. The remainder of the solar energy is reflected away and conducted across the greenhouse layer to maintain the elevated subsurface temperature. I then calculate that a collector 30 km (18 mi) in radius would be needed to reach a limiting temperature of 41 K. I have further assumed in this this calculation that the porous layer is very deep. It is more likely that the layer of high effective conductivity is relatively thin; in any event, the Tritonian summer is not long enough for thermal steady state to be reached in a layer thicker than a few hundred meters (1000 ft). Smaller collectors can reach the limiting temperature if the porous layer is thin. For example, if the layer is 100 m (330 ft) thick, a collector 3 km (2 mi) in radius suffices. This size is comparable with that of the dark spots seen at the bases of the active geysers on Triton.

An interesting feature of these reservoir models is that, although energy is transported primarily by gas flow, it is stored mainly as sensible heat in the solid matrix. The amount of pressurized gas actually present in the pore spaces when the reservoir is tapped is much less than the amount that can be released by evaporation and cooling of the warm solid nitrogen.

The steady-state power that can be delivered to a geyser in the center of the collector region is a function of the effective conductivity, the geyser radius, the maximum subsurface temperature, and the thickness of the porous layer. As we have seen, the maximum temperature reaches a limiting value for large collectors that we will assume to be 41 K. It is convenient that the effect of the porous layer thickness largely cancels out: in a thinner layer, energy is fed to the geyser through a smaller area, but the thermal gradients are correspondingly larger. For a given permeability, the power delivered to the geyser increases linearly with the geyser radius. Requiring that this power suffice to evaporate 20 kg of nitrogen (the estimated amount of gas erupting from the active geysers) per second, I find that a geyser radius of 400–600 m (1400–2000 ft) is needed, depending on the exact numerical model I choose. These values are 10 times less than the required radius of a "leaky greenhouse" with no lateral energy transport below the surface, but they are still 10 times greater than the estimated source radius of the active plumes. The calculated radius is decreased if the effective conductivity is larger, but, as discussed above, I have already assumed a very large permeability for the subsurface layer. According to the permeability-grain size relation I have used, a grain size of 6 m is needed to reduce the required geyser radius to 50 m.

Discussion The following conclusions can be drawn from the work I have outlined. First, for the Tritonian geysers to be solar powered, they must have a very efficient means of transporting energy from a large collector region to a much smaller geyser source area. Second, such an energy-transport mechanism may exist in the form of gas flow through a porous subsurface layer; the permeability I have assumed for this layer is admittedly very large, but it might be maintained by fracturing due to seasonal phase changes in the solid nitrogen. Third, thermal modeling indicates that, despite the efficiency of the gas in transporting heat away, a reservoir at the required temperature can be established under a collector of modest size (a few kilometers in radius) provided the permeable layer is relatively thin. Finally, the thermal models also suggest that the gas-phase energy transport is probably not efficient enough to deliver the power required for a geyser to a small enough source region in steady state. Clearly, the next step is to examine time-dependent models, in which a geyser taps a pre-existing reservoir. The initial output of energy and gas will exceed the steady-state value, allowing the requirements for geyser radius, permeability, or both to be relaxed. It is also of interest to see whether time-dependent models can predict the estimated active life span of the eruptions (5–10 Earth years). A preliminary scaling calculation is encouraging in this respect: 5 years is about the time required for gas flow to extract the excess energy from a region about 100 m across. The length of time for which a geyser erupts most actively may thus be determined by the time required to extract the thermal energy (in excess of that of the steady state eventually achieved) in the area immediately surrounding the vent.