Lecture 6: Enceladus A. P. Ingersoll api@gps.caltech.edu

1. Enceladus is a small moon (diameter = 500 km) in the outer solar system (average surface temperature = 75 K). The surface is water ice, which is hard as granite at these temperatures. The vapor pressure at these temperatures is essentially zero. You would expect it to be geologically dead – covered with craters and no other features.

2. Instead Voyager found evidence that the craters were being covered up. Either flow of a liquid or fallout of particles from a volcanic plume. Cassini has been in orbit around Saturn since 2004, and every few months there is a close approach to Enceladus. They have found a lot of geological activity. I would like to tell you about the observations and some of the modeling. The big questions are still unanswered: How is the energy generated? Is there liquid water in the interior? Is the liquid water in contact with warm rock? The last question is important for life, because life needs chemical energy and nutrients, not just water.

3. The first flyby did not have any images, but it did show an anomaly in the magnetic field. The interpretation is that the spacecraft had flown through a cloud of gas that was being ionized by UV radiation. Moreover, the gas was concentrated around the south pole.

4. The next flyby revealed plumes of solid particles, many with velocities greater than the escape velocity, which is 235 m/s. For comparison, the thermal velocity of water vapor molecules $(kT/m)^{1/2}$ is 300 m/s at T = 200 K.

5. As the spacecraft flew past, it took pictures of the plumes from different angles, and it was possible to located the sources of the plumes on the surface.

6. The sources turned out to be these five cracks, called tiger stripes. The south pole is in the middle of the tiger stripes, near the bottom of the image.

7. The plume sources are in red. The yellow places are hot spots measured by the infrared radiometer on the Cassini spacecraft.

8. Here are the first infrared scans. The upper box (a) is the long range view. It shows that the south pole is anomalously warm. This view allows one to estimate the total power from the south pole, which must be coming from the interior of Enceladus, because it is much greater than the absorbed sunlight. The lower box (b) shows the south pole in greater detail. Panels (c) – (f) show attempts to fit the spectrum of the infrared radiation. You can't do it with a single blackbody. You need a mixture of temperatures. The best fit to this spectrum has a high temperature component (T = 133 K) covering a few % of each pixel. This high temperature component is too small to be resolved.

9. More infrared scans. One pixel right over the tiger stripe has an average brightness temperature of 91 K, but the spectrum implies a component at 145 K covering ~4% of the field of view.

10. This is a thermal map of the south polar region. The tiger stripes are the warm places. Every point inside the box was mapped.

11. Here is one of the tiger stripes up close. The width is 1-2 km.

12. This is the closest image. It reveals boulders in the 20-50 m size range. No one understands where the boulders come from.

13. The camera went back and took another picture of the flow feature in the voyager image.

14. It's not clear if the craters were covered by a flowing liquid or fallout from the plumes.

15. The near infrared instrument took these images, which reveal mostly water ice but also organics in the vicinity of the tiger stripes. 3.44 microns is the wavelength of the vibration of a C-H molecular bond.

16. The UV spectrometer followed two stars as they passed behind Enceladus. One star passed through the plum.

17. There was dip in the starlight before the star passed behind the solid surface

18. Here's the spectrum of the light compared to a spectrum of water vapor. Use this to measure the density of the vapor in the plume.

19. Besides the remote sensing instruments, Cassini carried instruments that sampled the gases and particles directly.

20. The mass spectrometer detected peaks at mass 18 (water vapor), mass 44 (carbon dioxide), mass 16 (methane) and mass 28 (either CO or N_2). Further analysis reveals acetylene, propane, and maybe benzene (C_6H_6).

21. Here's a summary of what we know.

22. Here's a summary of what we would like to know. The big question is whether there is liquid water close to the surface. Actually, there are many big questions, like how is the heat generated, but I won't address them today. It has to be tidal heating, but so far, the models have failed to find the power by factors of 3 or 4.

23. Here's a model that produces the power, but it is inconsistent with the long-term evolution of Enceladus in its orbit. It is also too cold, in my opinion, because they

overestimated the thermal conductivity of the porous ice. The heat flux is known, so the temperature is inversely proportional to the thermal conductivity.

24. The problem is that the vapor in the pores is saturated at the temperature of the ice. At cold temperatures the vapor pressure is very low, and the porous ice can't carry the observed heat flux. It has to warm up. The question is, does it melt?

25. Besides diffusion in porous ice, the other way to get the heat out is hydrodynamic flow of vapor in cracks. So I have been looking at this problem, using ideas from rocket nozzles and high speed flow in pipes. The difference is that the fluid is exchanging mass, momentum, and energy with the walls.

26. A few results. There is a supersonic solution – the smooth curve, and many subsonic solutions – the bent curves, but they are unstable. By adjusting the power and the width of the cracks, you can match the speed of the gas at the vents and the size of the particles.

27. The main point is that the crack has to be wider than 10 cm to get the heat out, and it helps to have several cracks per tiger stripe.

28. Summary of results. Heat generated away from the cracks has to get out by diffusion in a porous medium, but the pores have to be large – particle size > 1 mm, and that is unlikely. Instead, the ice will flow and the pores will close up due to hydrostatic pressure on the grains. Heat generated on the sides of the crack can get out by hydrodynamic flow provided the crack is wide enough (width > 10 cm). If the heat can't get out as vapor, the ice will melt, and it will come out as liquid. The basic result is that we don't know the conditions below the surface.

29. Let's be optimists and assume the ice does melt. What are the possibilities for life?

30. Liquid water is not enough. Life requires nutrients, not just C, H, O, N, but also Fe, P, Mn, and many other elements. It would help if the liquid water were in contact with rock.

31. Life also requires energy. Without sunlight, life can get energy from the oxidation state of the rocks. This is life at the bottom of the ocean.

32. This is life in sedimentary rocks at 1 km depth. There's more we can learn about Enceladus with Cassini. Stay tuned.

33.. The end.