Lecture 3: Small Objects A. P. Ingersoll api@gps.caltech.edu

1. Some of these objects are planets, some are satellites of planets. Some of these atmospheres are thick (mean free path much less than the atmospheric scale height), and some are thick. Except for Titan, all the atmospheres are controlled by the vapor pressure of a frost on the surface.

2. The last column gives the gravitational binding energy divided by the thermal energy of a molecule = (escape velocity/thermal velocity)^2. The units are arbitrary, but it gives a crude measure of which objects are more likely to retain an atmosphere and which are less likely. Ganymede should have an atmosphere if Io, Triton, and Pluto do, but it doesn't have one. Mercury and Earth's moon have exospheres – atmospheres so thin that the molecules don't collide with each other; they just collide with the surface.

3. Start with Titan – the largest moon of Saturn. This is the Voyager view in visible light. Covered with clouds and haze. You can see the surface at 0.5 microns, although you can see it at 0.95 microns.

4. Titan with the Sun behind the object. The gravity is low, so the scale height is large, and the atmosphere does not have a sharp limb – the edge looks "fuzzy."

5. Mostly molecular nitrogen, N_2 (90 – 97%), argon Ar (0 – 6%), and methane CH_4 (0.5 – 4%). The range for nitrogen and argon is an uncertainty. The range for methane is temporal and spatial variability.

6. Vertical structure. Temperatures were measured by Voyager radio occultation (sending a radio beam tangentially through the atmosphere) and by the Huygens probe, which parachuted to the surface and measured T, P, composition, images.

7. Methane is being destroyed by UV light from the Sun. The hydrogen escapes from the gravity field of Titan, and the remaining C and H atoms form higher hydrocarbons. The photodissociation rate of CH_4 and the escape rate of H have been measured. This raises two problems: (1) Titan's surface should be covered with hydrocarbon lakes 100 meters deep. (2) There must be a subsurface source of methane that is still active. These problems have not been solved.

8. Titan has a hydrologic cycle, but the condensable gas is methane. There are two major differences from Earth. (1) No ocean, so large parts of the surface should dry out, unless there is a global aquifer that moves the methane around. (2) The latent heat stored in the methane vapor is large and the power supply is small, so the vapor residence time is very long. M is the mass/area of condensable in the atmosphere, ML is the latent heat/area. F_{surf} is the solar power/area at the surface. τ_v is the vapor residence time – the time it would take to re-charge the atmosphere if

it should all rain out. Heavy rain should be infrequent, or else you have nothing but mild drizzle (mist).

9. There is evidence of erosion, so there must be heavy rains. We don't know how old these features are. They could be hundreds or thousands of years old.

10. Looks like Los Angeles as you fly in over the ocean. The smooth dark areas are not liquid. These images were taken by the Huygens lander as it parachuted to the surface.

11. Rounded boulders (of water ice at 92 K). They look like boulders from the bottom of a stream bed - evidence of erosion.

12. Synthetic aperture radar (SAR) can see through the clouds. The radar beam is not looking straight down, so a smooth surface reflects the beam off in a different direction. Liquids look dark (colored blue in this image), and rough surfaces look bright (colored yellow in this image).

13. This is a more honest image, because it has no color, but it is just as interesting.

14. These are images from Earth – the Keck telescope with adaptive optics. They show clouds near the summer pole over a 2 Earth-month period. The cloud activity stopped one Titan month after summer solstice. Titan's year is the same as Saturn's: 30 Earth years.

15. These are images taken by the Cassini orbiter as one of the cloud outbursts was ending. They look like cumulus clouds, which is consistent with moist convection.

16. Sand dunes on the surface as seen by the radar from the Cassini orbiter. The material of the dunes may be water ice contaminated by hydrocarbons.

17. More sand dunes. Morphology and GCM estimates of wind suggest the dunes are longitudinal – they run parallel to the wind (mostly east-west).

18. Dry lakes. The liquid either evaporates or soaks into the underground aquifer.

19. Evaporation minus precipitation for Earth, measured in cm/year. The excess precipitation that falls in the tropics and high latitudes flows into the oceans, which supply the evaporation in the sub-tropics (10 - 30° latitudes).

20. Results from a GCM of Titan's atmosphere. They assumed that liquid methane was present on the surface at all latitudes. This could be a bad assumption if there is no underground aquifer. Another problem with this model is that the global precipitation exceeds the global evaporation. The hydrologic cycle does not balance.

In fairness to the authors, they published the model before the Cassin-Huygens reached the planet and returned data [Tokano etal, Icarus 153, 130-147 (2001)].

21. Wind profile measured by Huygens using the Doppler shift of the radio signal. At 40 km altitude the speed is 20 m/s; at 140 km the speed is over 100 m/s. This is faster than the jet streams on Earth, even though the solar power is 1% that reaching the Earth.

22. GCM results for wind and temperature – much less activity than the real atmosphere.

23. There is a cross-equatorial Hadley cell with rising motion in the summer hemisphere. Because the rotation is slow (one Titan day = 16 Earth days), the Hadley cell extends to high latitudes.

24. Talk now about objects with thin atmosphere. Mercury and the Moon have exospheres – probably molecules sputtered off the surface by energetic particles. Pluto and Triton have nitrogen atmospheres controlled by frost on the surface. Io has a SO_2 atmosphere on the day side; it is controlled by surface frosts and by volcanoes.

25. This is Mars, which has a CO_2 atmosphere that is controlled by surface frosts. The atmosphere is massive enough that it only drops by 30% during winter in each hemisphere.

26. This is a model of Pluto's N_2 atmosphere. Shaded areas in the lower curve are frost. The white areas are frost-free. Pluto's year is ~200 Earth years. The sinusoidal line is the latitude of the Sun as seen from Pluto's surface. Perihelion (Pluto closest to the Sun) occurs during northern spring, so the rising portion is steeper than the falling portion. Pluto's obliquity (tilt of its spin axis) is 60°, so the frost caps reach much lower latitudes than they do on Earth. The upper panel shows the atmospheric pressure; it varies by orders of magnitude during the year. The atmosphere collapses twice per year. This is for case when the surface has low thermal inertia. It heats up and cools down on a short time scale – short compared to the seasonal cycle. [Hansen and Paige, Icarus 120, 247-265 (1996)].

27. This is for a high thermal inertia. The surface doesn't respond to the seasonal cycle. There is a permanent frost band around the equator. Averaged over the year, the poles get more sunlight than the equator because the obliquity is so large. Once the ground is frost-free, its low albedo keeps it warm, and frost cannot get started. The atmospheric pressure is nearly constant.

28. This is Triton – the largest moon of Neptune. The spin is right handed about the southern pole, which is the one that you see. When Voyager took this image, it was summer in the southern hemisphere. The streaks probably left over from the

southern spring season. They are the remains of active vents of hydrocarbons and nitrogen vapor that were blown downstream by the wind as the frost was evaporating. The diagonal orientation is consistent with equatorward flow (upward in this image) in an Ekman layer. The flow developed a component opposite to the direction of rotation, which is to the right in this image. So you have streaks that slope upward and to the right. [Ingersoll, Nature 344, 315-317 (1990)].

29. Another look at the streaks. The pole is off to the left, and the spin is counterclockwise around that pole.

30. Io is the volcanic moon of Jupiter. Voyager discovered SO_2 in the atmosphere, but the vapor pressure is so low that SO_2 vapor can only exist on the day side and under a volcanic vent.

31. The particles and vapor are thrown up to altitudes of 500 km

32. The lava lakes are hotter than most molten silicates on Earth (1800 K), implying high magnesium content.

33. The satellites Europa and Ganymede do not allow Io to settle into a circular orbit. This means that Io is constantly being stretched and pulled, which generates a huge amount of internal heat for a small body of its size.

34. Horizontal flow from the day side to the night side involves a gas expanding into a vacuum. Like a rocket nozzle, the gas can convert all of its initial enthalpy into kinetic energy, reaching supersonic speeds if it goes through a choke point. In a rocket nozzle the choke is the narrowest part of the conduit – where the flow changes from contraction to expansion. On Io the flow is contracting near the sub-solar point because the surface is adding mass to the flow (evaporation rate $E > 0$). The flow is expanding beyond this point because the surface is removing mass from the flow ($E < 0$). [Ingersoll etal, Icarus 64, 375-390 (1985)].

35. Radar images of Mercury's north and south poles. The poles are visible from Earth (at a low incidence angle) because Mercury's orbit is tipped 11° relative to the Earth's orbit. The high radar reflectivity is characteristic of ice or other transparent material.

36. The bright areas coincide with craters at the pole. Mercury has zero obliquity, so the Sun never shines into these craters. Their temperatures are always less than 90 K. At these temperatures, water ice is stable for the age of the solar system. Current thinking is that a comet strikes the surface of Mercury and vaporizes. The molecules hop around the hot surface. Many of them get ionized and carried away in the solar wind, but a few hop randomly into these cold traps. There they accumulate for long periods of time. Although the Sun never shines in these craters, they do get struck by meteorites. The frost may be in steady state balance between production and loss.