Lecture 2: Mars A. P. Ingersoll api@gps.caltech.edu

1. The three main elements of the weather are CO_2 , water, and dust. CO_2 is the main constituent of the atmosphere, and unlike nitrogen and oxygen on Earth, it fluctuates by 30% every year due to condensation at the poles. Water, especially liquid water, is of potential biological interest, but the total pressure is so low that water boils at 0 C. Dust accounts for the largest changes in the weather, and is highly unpredictable.

2. Here you can see ice clouds, which are probably water, and the northern ice cap. Light and dark markings are permanent, but they get covered by dust sometimes.

3. The same face of Mars before and during a global dust storm. The dust storms are like El Nino; they happen at a certain time of year (southern spring for the dust storms), but they don't happen every year. Unlike Earth, there is no ocean to explain the interannual variability.

4. Topography of Mars. The mountains are higher than on Earth because the gravity is lower – the strength of the rocks is the same. The topography is almost as large as the atmospheric scale height, making the atmosphere like an ocean basin.

5. Like Venus, the atmosphere is mostly CO_2, but there are small amounts of other gases: nitrogen 2.7%, argon 1.6%, CO 0.1% (these numbers add up to 99.7%). The mean surface pressure is only ~7 mbar, which is the vapor pressure of CO_2 ice at T of 148 K. The polar caps get this cold in the winter, and CO_2 condenses out [figure is from de Pater and Lissauer]

6. The north *residual* polar cap – the way it looks in mid summer after the seasonal covering of CO_2 has gone away. The temperature is much higher than 148 K (~ 205 K), indicating that it cannot be CO_2 ice. The spectral features of water are prominent, and the atmosphere is saturated with respect to water at ~205 K, so the residual cap is water.

7. The south residual polar cap. The composition is not so obvious. The temperature is lower, the water spectral features are less obvious, and the atmospheric water is less abundant in southern summer compared to northern summer.

8. The classic model is by Leighton and Murray [Science 153, 136-144 (1966)], but there are problems. They assumed that most of the CO_2 on Mars is in the polar caps. The temperature of the polar caps determines the vapor pressure of CO_2 in the atmosphere. The polar caps are the reservoir that buffers the atmosphere. The problem is that the seasonal frost disappears faster than their model would predict. The observations suggest that it is gone by the first day of summer (L_s is the angular position of Mars in its orbit. L_s = 0 is the first day of northern spring). If the residual polar caps were CO_2 , they would be losing net mass from one year to the next.

9. The growth and retreat of the polar caps is reflected in the fall and rise of the atmospheric pressure. Viking lander 1 was at a higher elevation than Viking lander 2, so its pressure is lower. There are two minima per year because there are two polar caps that are out of phase with each other.

10. The polar cap mass balance is mostly just latent heat release as the cap grows, which is balanced by the loss of heat as longwave radiation minus the gain of heat from absorbed sunlight (sunlight is zero during the winter). By adjusting the albedo and emissivity of the CO_2 frost, it is possible to match the seasonal pressure curves, but then the cap is losing mass from one year to the next. This is the same problem revealed in the visible observations of the growth and retreat of the cap. This problem can be summarized as follows: (1) The residual CO_2 ice cap is losing mass, and (2) there is an extra heat source that is causing less CO_2 to form during the winter or is causing it to evaporate faster during the spring. The authors have an explanation for (2), which is heat stored in the water ice below the CO_2 seasonal frost cover, but they don't have an explanation for (1). [Haberle etal Planet and Space Sci, 58, 251-255 (2008)]

11. Another group fitting the CO_2 pressure data from the Viking landers. Both groups use a full general circulation model (GCM). Kuroda etal have the same problem: The observed retreat of the polar cap from visual observations is faster than the model would predict. [Kuroda etal, J. Meteor Soc. Japan, 83, 1-19, (2005)]

12. A close look at the residual southern cap, the one that might be CO_2. The sun is to the upper left. These are circular depressions. The flat topped surfaces are the highest. Called the Swiss Cheese Terrain because it has holes.

13. Change from year to year. The holes are growing in diameter (at the rate of several meter per year) but not in depth. All the flat topped surfaces will be gone in 100-300 years, which is very strange. It looks as if the flat topped surfaces were created just 100-300 years ago.

14. Dust may be involved. The sun is to the upper left. The image on the right is earlier (southern spring). The image on the left is later (southern summer). Notice the dark material on the sides of the depressions during summer.

15. Another example of changes from spring to summer. The flat topped surface has almost disappeared as its walls evaporate. This material must be CO_2 ice. It cannot be water ice because water evaporates too slowly at these low temperatures.

16. Warmer temperatures indicate water ice at the bottoms of the circular depressions. Maybe the flat topped material is CO_2 (it is only 8-10 m thick), and the remaining 3 km of the south residual polar cap is water ice [Byrne and Ingersoll, Geophys Res. Lett. 30, 1696-1699 (2003)]

17. Sunlight seems to control the shape of the depressions. They often have a "C" shape with the opening pointing north (toward the sun). The uniform size suggests they all started growing at the same time (80-400 terrestrial years ago). It seems the Leighton and Murray model is wrong: There is no large reservoir of CO_2 at the poles. Instead it is a layer 8-10 meters thick, which is going to disappear in a few hundred years. This will raise the atmospheric pressure by a small amount (5%). Why does Mars have so little CO_2 compared to Earth and Venus? [Byrne and Ingersoll, Science 299, 1051-1053 (203)]

18. Change the subject. Measure the atmospheric temperature and compute the winds from the thermal wind equation, assuming the wind is zero at the surface. The winter pole gets very cold (upper left). [Zurek etal, in Mars, H. H. Kieffer etal, Eds. U Arizona, 1992]

19. Model the winds with a GCM. They do a good job with the zonal mean. [Kuroda etal, J. Meteor Soc. Japan, 83, 1-19, (2005)]

20. Models do a good job at simulating clouds. These are water ice clouds at the equator This is the NASA/Ames GCM. [Malin et al, Icarus 194, 501-512 (2008)]

21. Water ice clouds over volcanoes. The air is lifted by the topography and condenses as it cools.

22. Except for dust storms, the weather is very repeatable. The diurnal cycle dominates because the atmosphere is so thin. Baroclinic waves are less important than they are on Earth.

23. Dust storm and ice clouds together.

24. Evidence that water once flowed in the distant past. The impact craters indicate that the surface is > 1 billion years old.

25. Further evidence that water once flowed in the distant past.

26. Gullies suggest water flowing from an underground source in the recent past (no craters, unstable hillside)

27. More evidence. This subject gets a lot of debate. One problem is that water at 0°C (pressure of the vapor = 6.1 mbar) is close to the boiling point. Even if it doesn't boil, it will evaporate very fast because the lighter water molecules will be buoyant in the heavier CO_2 gas. Any frost that forms overnight will sublimate without melting as soon as the sun hits it [Ingersoll, Science 168, 972-973 (1970)]

28. Water vapor in the atmosphere vs season (L_s = 0-90 is northern spring). There is uncertainty about whether the water comes from the frost cap or from the dark area around the cap, perhaps left over from the previous winter.

29. Dust devils photographed from a lander on the surface of Mars

30. Dust devil tracks

31. Sand dunes. The question is, why do global dust storms occur every few years? Why not every year?

32. El Nino involves a movement of warm water from the western Pacific to the Eastern Pacific. The period of this oscillation is longer than a year, so El Ninos do not occur every year. The analogy breaks down, because Mars has no ocean.

33. Dust has a positive feedback on the atmospheric circulation. The dust absorbs sunlight and heats the air by a large amount because the atmospheric density is so low. The heated air rises and generates pressure gradients, which drive the winds and pick up more dust. [Basu etal, J. Geophys. Res. 111 (E9), 2006]

34. Another figure from Basu etal (2006). This dust storm started in a deep circular basin (Hellas), and spread quickly in longitude (1st and 3rd columns). The source of the dust remained mostly in Hellas, although one or two secondary lifting centers developed (2nd and 4th columns).

35. Another figure from Basu etal (2006). The model has a threshold wind speed for picking up dust. If the threshold is too low (τ = 0.040 Pa), you get a dust storm every year (top panel). If it is too high (τ = 0.058 Pa), you never get a dust storm (bottom panel; year 1 is the exception because it depends on the initial conditions). Interannual variability occurs only in a narrow range of the threshold wind speed. Why should Mars be within this range? Maybe it organizes itself.

36. A simple 12-parameter model of a Hadley circulation with dust. This is an example of self-organized criticality. The threshold wind speed depends on the recent history – it is high after a major dust storm, and it takes more than a year for the threshold to fall to the point where dust storms occur again. The threshold wind speed is high when the windy places are bare, and it is low when the windy places are covered with dust. In this example, the initial conditions are dusty, and there is a dust storm every year until a balance is obtained where the time between dust storms is equal to the time for the threshold to fall to the point where dust storms occur. [Pankine and Ingersoll Icarus 170, 514-518 (2004)]

37. Same model, but now the initial value of the threshold is too high and no dust storms occur until the threshold falls to the point where dust storms occur. They do not occur every year because it takes more than a year for the system to recover

after a major dust storm. The bottom panel shows that the number of years between dust storms is a random variable. Weather noise creates the randomness. The behavior in the balanced state is independent of the initial conditions.