Lecture 5: Saturn, Neptune, … A. P. Ingersoll api@gps.caltech.edu

1. A lot a new material from the Cassini spacecraft, which has been in orbit around Saturn for four years. This talk will have a lot of pictures, not so much models.

2. Uranus on the left, Neptune on the right. Uranus spins on its side. The obliquity is 98 degrees, which means the poles receive more sunlight than the equator. It also means the sun is almost overhead at the pole during summer solstice. Despite these extreme changes in the distribution of sunlight, Uranus is a banded planet. The rotation dominates the winds and cloud structure.

3. Saturn is covered by a layer of clouds and haze, so it is hard to see the features. Storms are less frequent on Saturn than on Jupiter; it is not just that clouds and haze makes the storms less visible. Saturn is a less active planet. Nevertheless the winds are stronger than the winds of Jupiter.

4. The thickness of the atmosphere is inversely proportional to gravity. The zero of altitude is where the pressure is 100 mbar. Uranus and Neptune are so cold that CH forms clouds. The clouds of NH_3 , NH_4SH, and H_2O form at much deeper levels and have not been detected.

5. Surprising fact: The winds increase as you move outward in the solar system. Why? My theory is that power/area is smaller, small-scale turbulence is weaker, dissipation is less, and the winds are stronger. Jupiter looks more turbulent, and it has the smallest winds. Uranus and Neptune have retrograde winds at the equator. Jupiter and Saturn have prograde winds. No good explanation for that.

6. All four giant planets have temperatures controlled by the winds. The zonal jets decay with altitude in the region above the clouds. The equator-to-pole temperature differences are small.

7. Saturn's winds measured in 1980 and 2004. Maybe some change at the equator, but that might be due to change in cloud height coupled with vertical wind shear. The westward jet at 35 degrees South has been the most active during the past four years. Winds are measured relative to a rotating reference frame based on Voyager radio data. We would like to use the wobble of the magnetic field, but Saturn's field doesn't wobble. It is aligned parallel to the rotation axis. We really don't have a good reference frame for the winds.

8. The last time Saturn had a large storm like this was in 1994. Large storms are extremely rare, unlike Jupiter. The storms do not form permanent vortices. They appear suddenly and dissipate in a month or two.

9. The northern hemisphere has been in the shadow of the rings for 10 years. This is an image when the spacecraft was in the plane of the rings. The rings are the thin straight line in the center. The northern hemisphere has less clouds and haze, and it

is possible to measure the Reynolds stress, u'v' which is the same direction as on Jupiter: The eddies are putting momentum into the zonal jets [Delgenio et al 2007]

10. Storms in the westward jet at 35°S.

11. Merging of spots at 35°S.

12. A view of the night side of Saturn. It is never completely dark because the rings are always shining. This makes it hard to see lightning. We cannot tell the difference between lightning flashes and clouds illuminated by light from the rings.

13. The spacecraft detects the radio signals from lightning (SED = Saturn electrostatic discharge). These happen about once per year. The active period lasts for a few weeks or a month. During the active period, the flashes occur at the rate of several per minute.

14. Each time the SED activity begins, we look for a storm. The top panel shows one side of Saturn with a small white storm. The bottom panel shows the other side of the planet.

15. Cassini detects the radio signals only when the storm is on the side of the planet facing the spacecraft. The upper box shows the SED's in a reference frame based on the storm that we see. This is evidence that the storm is causing the SED's [Dyudina et al, Icarus 190, 545-555 (2007)]

16. Another view of the storm. It changes shape every day – like one of the active places on Jupiter, but there is only one storm on the planet at any one time.

17. Evolution of the storm over a 25-day period.

18. A new subject – the south polar vortex. This is an Earth-based view in the infrared, showing a small hot spot over the south pole. The season is summer in the south.

19. Here is the south pole in visible light. The colors were chosen to indicate clouds heights. Pink = low clouds, green = high clouds and haze.

20. The inner ring is 1 degree from the pole (2000 km diameter). The arrows show the direction of sunlight. The clouds cast shadows, which allows us to estimate the heights of the clouds (Dyudina et al, Science 319, 1801 (2008)]

21. The clouds are high – up to 75 km, which is much higher than the eyewall clouds of a terrestrial hurricane. In units of pressure scale height, it is about the same – two scale heights in each case4

22. Another view of the inner ring. The sun is in the upper right.

23. A high-resolution view. The ring has a diameter of 2000 km.

24. A movie showing the cyclonic (clockwise in the southern hemisphere) motion around the pole. This is opposite from what the models predict for barotropic turbulence on a sphere. Baroclinic effects may be important.

25. Measured winds. The large-scale flow is cyclonic (clockwise), but the small spots are spinning counterclockwise as they go around the pole. Counterclockwise means anticyclonic, which is consistent with horizontal divergence at the top of the clouds, which is consistent with convection. The solid lines in the top panel are for constant absolute vorticity – constant $\zeta + f$. The line in the bottom panel is the measured large-scale vorticity ζ, which is nearly zero up to latitude 88°. The cyclonic vorticity is concentrated in the center. This resembles a Rankine vortex.

26. Temperatures in the vortex are warm, like the eye of a terrestrial typhoon. The cyclonic vorticity, the ring of high clouds, and the small convective clouds outside the ring are also similar to a terrestrial typhoon. The differences are that it is locked to the pole, and is not interacting with an ocean underneath. The interaction with the deep atmosphere is unknown, although it might have some similarities with that of a typhoon.

27. The north pole has a hexagon at 75°N. The diameter is 30,000 km. It was discovered by Voyager in 1981, and is still present in 2008. There is also a hot spot of diameter ~2000 km, like the south polar hot spot (Kevin Baines)

28. The hexagon is a standing wave in an eastward jet whose speed is ~100 m/s relative to the clouds at neighboring latitudes. Remember that we can only measure *relative* winds on Saturn, since we don't know the rotation rate of the interior.

29. Here the eye of a typhoon. Usually they are circular. This one is a polygon. The diameter is 50 km.

30. Infrared image of the polar vortex on Venus, compiled by Sanjay Limaye and Fred Taylor. Many similarities with the Saturn vortex, but there are no convective clouds around the outside of the Venus vortex.

31. The Venus vortex is more irregular. The terrestrial polar vortex is a cold core vortex brought on by radiative cooling during the winter.

32. New subject: The QBO on Saturn. These infrared images were taken from Earth by Glenn Orton. Notice that the band at 13°S has changed its temperature during the 9 year interval.

33. Temperature difference between the equator and the band at 13°S as a function of time. Period is about 18 years, which is less than Saturn's orbit period of 30 years.

34. QBO on Earth. A periodic reversal of the zonal wind in the equatorial stratosphere.

35. Cross section (latitude-altitude) of temperatures in the equatorial stratosphere of Saturn.

36. Zonal winds computed from the thermal wind equation. The oscillation with height is similar to the oscillation of the QBO.

37. New subject: Neptune. The first part is a five-day movie of a solid planet. The second takes the motion at different latitudes into account. The third part shows how we pointed the camera to capture the spots using data that we taken 2 weeks earlier. The fourth part show the motion of the great dark spot.

38. A model of the Great Dark Spot – the Kida vortex model. It consists of an inviscid barotropic fluid on a plane. The outside fluid has constant vorticity q_B and the fluid in the center has constant vorticity q_V. [Polvani et al Science 249, 1393-1398 (1990)]. The ratio of the q's determines the behavior of the vortex.

39. The equations were discovered by Kida.. λ is the ratio of short axis to long axis of the ellipse. φ is the angle with respect to the east-west line. The background flow is a simple shear. There are four parameters: the two values of vorticity and the initial conditions on λ and φ.

40. Here is the fit to λ. Having chosen the parameters to fit the oscillation in λ, no adjustments are possible to fit the oscillation in φ, and still the fit is very good.

41. Here is the fit to φ. It captures the amplitude, the period, and the tilt of the curve, all with no free parameters.

42. Last subject – extrasolar planets. The number grows every week and is now close to 300. Most have been detected by the Doppler shift they give to the starlight. The signal is large when the planet is large and close to the star.

43. An example of the velocity curve from a "hot Jupiter" The orbital period is 4.23 days, which means it would be inside the orbit of Mercury. The lower bound on the mass is 0.44 times the mass of Jupiter. The uncertainty is because we don't know the angle between the orbit and the line of sight.

44. A small fraction of the objects cross in front and behind the parent star (they "transit"), which allows us to determine the mass, radius, albedo, temperature, and a little bit about the composition of the extrasolar planet.

45. There are some surprises. Many of the extrasolar planets are larger than the models would predict. This is an active field.