Lecture 4: Jupiter A. P. Ingersoll api@gps.caltech.edu

1. Jupiter is a big topic. We will talk about the composition of the atmosphere, lightning, the zonal jets, and the long-lived vortices. The Great Red Spot was visible in the first telescopes more than 300 years ago.

2. The cloud bands change very little from Voyager time to Cassini time. The chemicals that cause the different colors have not been identified. The most likely chemicals are organic compounds and sulfur compounds. The bands follow lines of constant latitude, which shows that the rotation of the planet is controlling the orientation of the bands.

3. The first topic is the composition of the gases in Jupiter's atmosphere. The column labeled "sun" is what you would get if you cooled a piece of the sun down to Jupiter's temperature. The elements would combine with hydrogen to form water, methane, ammonia, and hydrogen sulfide. The noble gases would not combine. The column labeled "Jupiter" shows the measured values, which are about 3 x solar, or three times what you would get by cooling a piece of the sun.

4. Most of the measurements come from the Galileo entry probe, which had a mass spectrometer that took data from 1 bar to 20 bar. Most elements are 3 x solar. Helium and neon probably separated into the core. Most people think that oxygen was removed as water from the place where the probe went in, but it is possible that oxygen is less abundant than 3 x solar. In order to get all these elements to have the same enrichment factors relative to solar, Jupiter must have received its volatiles as icy planetesimals that formed at temperatures below 40 K.

5. One puzzle is that the measured abundances of ammonia, H_2S, and water (left) do not follow a model based on their saturation vapor pressures (right). The model assumes that the deep atmosphere is well mixed and is representative of the planet as a whole. The water abundance of the deep atmosphere is uncertain. The spacecraft died while the abundance was still rising.

6. The problem may be that the Galileo probe went into a "hot spot," which is a giant hole in the clouds. It looks hot because infrared radiation escapes from deeper levels. This is a 5 micron image (wavelength = 5×10^{-6} m), where the gases in the atmosphere are transparent. There is a hot spot in the bright band just north of the equator.

7. Here is a hot spot in visible light. It looks dark because there are no clouds to reflect the sunlight. The clouds are made of NH_3, H_2S, and H_2O. No clouds means low abundances of these gases. The hot spot might be a place where dry air from the stratosphere has been pushed downward.

8. Showman etal demonstrated that a wave with vertical excursions of 2-4 times the initial pressure (left) is more stable than one with smaller excursions (right).

[Showman et al, Science 289, 1737 (2000)]. These large vertical excursions could explain the depressed values of these compounds much deeper than the condensation levels.

9. Nakajima etal [Geophys. Res. Lett. 27, 3129-3132 (2000)] have a model of moist convection on Jupiter. They argue that the water condensation level (WCL), which occurs at 5-6 bars, should be very stable, since the molecular mass of water is greater than that of hydrogen. Dry air above = lower density = stable.

10. Here is the stability parameter N^2. Because N^2 is so large, it requires a large amount of energy to push low-density dry air down to 20 bars through the dense lower atmosphere with its large amount of water vapor. Showman etal did not take this effect into account. The alternative is that O/H on Jupiter is less than that on the sun, but that upsets theories of solar system formation.

11. Here are measurements of temperature based on the radio occultation method. The radio waves do not penetrate below 1 bar for Jupiter. The lower portion fits a dry adiabat, which is consistent with a convective troposphere.

12. Here is a model of the stratosphere and troposphere based on adiabatic lower atmosphere and solar abundances of N, S and O. The gases condense to form clouds of NH_3, NH_4SH, and H_2O. The water cloud is ~100 km below the top of the ammonia cloud. It is the thickest cloud, since water is the most abundant condensable vapor in a solar composition atmosphere.

13. This is a night side image of Jupiter showing moonlit clouds (light from Io makes the clouds visible in a long exposure of the camera). The bright spots are lightning. The image covers an area from the equator to a latitude of 50°. Repeated images over a day show the lightning is always coming from the same place, so these must be individual storms.

14. Here are 3 storms over a 2 minute period. The lightning flashes are different, but the storms are the same.

15. The lightning flashes are wide – about 150 km in diameter. We modeled this as a point source at an unknown depth below the tops of the cloud. The photons diffuse up through the cloud. You infer the depth from the width of the flashes, and the depth is at least 100 km. This means the lightning is in the water cloud or deeper.

16. Some facts about Jovian lightning. Some of the flashes are 3 times brighter than the brightest flashes on Earth, but the storms are farther apart, so the total optical power per unit area is ¾ the value for Earth. [Little etal Icarus 142, 306-323 (1999)]

17. Galileo was able to image the planet on the day side, and then image the same clouds several hours later when they were on the night side. The night side image

shows the lightning (red), and it is correlated with small bright clouds on the day side. [Dyudina et al 172, 24-36 (2004)]

18. These small bright clouds have lifetimes of a few days. Time increases from top to bottom. Each image is 20 hours later than the one above.

19. The lightning storms mostly occur in the dark bands, which are called "belts." The bright bands are called "zones." There are jet streams on the edges between the belts and the zones. The zones are anticyclonic (in the northern hemisphere, the zones have a eastward jet on the northern edge and a westward jet on the southern edge).

20. Here are the places where lightning was observed. Lightning occurs in the cyclonic belts. This is a puzzle because the dark belts are relatively cloud-free and the bright zones are relatively cloudy. Notice the multiple jet streams.

21. This is the traditional view, and it may be wrong. Updrafts in the zones produce clouds. Downdrafts in the belts produce clear areas. I added the arrows to show what might be happening at the base of the clouds. Updrafts in the belts produces lightning storms and moist convection. Why the circulation should reverse is a mystery.

22. Here is a 60-day movie of the northern hemisphere taken by Cassini. You can't see the pole because the spacecraft was only a few degrees above the equatorial plane. To make this movie, Ashwin Vasavada had to put ~1000 images together into a polar mosaic. The pole is in the center and the equator is in the corners. You can see at least 6 jet streams in the northern hemisphere.

23. Here is the same movie with better resolution. You see more detail at the end because the spacecraft was closer to Jupiter.

24. Here are the jet streams for Jupiter and Saturn. The winds are measured relative to the interior of the planet, based on the wobble of the magnetic field. Jupiter's field is tilted by 10°, which gives a nice wobble. The problem is that Saturn's field is not tilted, so we don't know the interior rotation. For Saturn, these winds are based on radio emissions detected by Voyager, and they may give the wrong rotation. The Galileo probe went in at 6.5° north latitude, where the wind at the top of the clouds (0.5 – 1.0 bar) is ~100 m/s. Notice that the winds are prograde (westerly) at the equator.

25. The winds increased with depth, which was a surprise, and then stayed constant until the probe died at 20 bars. These winds were determined by tracking the radio signal from the probe and measuring its Doppler shift.

26. Major differences between Jupiter and the Earth. (1) There is only one eastward jet stream in each hemisphere on Earth. The speed (upper panel on right) is ~30 m/s. (2) The emitted longwave radiation (upper panel on left) is low at the poles because it is colder at the poles than at the equator.

27. On the giant planets the poles are just about as warm as the equator. The small oscillations are associated with the jet streams. On small scales the temperature gradient $\partial T/\partial y$ changes sign with latitude, which means the wind shear $\partial u/\partial z$ changes sign, according to the thermal wind equation.

28. When you compare the wind shear computed from $\partial T/\partial y$ with the winds observed by tracking clouds, you find they are anti-correlated. The winds decay with height. This is in the upper troposphere (~300 mbar), where the temperatures are measured.

29. Models of jet formation. Rhines [J. Fluid Mech. 69, 417-443 (1975)] showed that turbulence on a rotating sphere, which he approximated by a beta-plane, will organize itself into jets. He argued that the turbulent eddies grow by merging until they reach a certain size, where Rossby wave radiation produces the jet. The wavenumber (inverse of the size) is or order $k_\beta = (\beta/U)^{1/2}$, which is now called the Rhines scale. Here $\beta = df/dy$ is the planetary vorticity gradient, and U is the typical velocity of the flow. Williams [J. Atmos. Sci. 35, 1399-1426 (1978)] applied these ideas to Jupiter. This is a time series of forced barotropic turbulence on a sphere.

30. Freely evolving turbulence on a sphere [Yoden et al, Il Nuovo Cimento 22, 803-812 (1999)]]. There is no forcing or dissipation. When the sphere is not rotating (left), the flow organizes itself into large vortices. When the rotation is large (right), the flow organizes itself into bands at constant latitude. Further integration leads to a single large vortex at the pole.

31. Cho and Polvani [Phys. Fluids 8, 1531-1552 (1996)] followed freely-evolving turbulence to its final end state. This figure is for non-divergent flow (infinite radius of deformation); there are no mid-latitude jets, just one anticyclonic polar vortex in each hemisphere. Absolute vorticity is constant within each polar vortex. For finite radius of deformation (not shown), there are bands and jets.

32. Li et al [Icarus 180, 113-123 (2006)] changed the small-scale forcing from a random isotropic pattern to one resembling the small-scale convection and lightning on Jupiter. Their forcing is only in the cyclonic regions – the belts, and it covers only a small fraction of the area at any one time. The results are the same. This is a quasi-geostrophic (QG) model, so it does not include the equator.

33. Notice the tilted clouds, especially in the dark bands – the belts. The tilt is in the same direction as the shear – counterclockwise in the belts in the northern hemisphere and clockwise in the belts in the southern hemisphere. If there is eddy

motion, northward and southward, along these tilted lines, it would imply a Reynolds stress $\rho\overline{u'v'}$ that increases the shear. The divergence of the Reynolds stress $\partial(\rho\overline{u'v'})/\partial y$ would increase the speed of the zonal jets.

34. Here are the measurements. The black is the shear $\partial u/\partial y$ and the red is $\overline{u'v'}$. The fact that they are correlated means that the eddies are putting energy into the jets. If the two curves were anti-correlated, it would mean that the eddies are taking energy out of the jets. The power per unit mass is about 2 x the rate on Earth. This energy conversion is large when you compare the power/area in sunlight at Earth and Jupiter (Earth's is 25 times greater).

35. Until recently, these experiments with forced turbulence on thin spherical shells (shallow water turbulence) have failed to match the observations in one important respect: The winds at the equator are retrograde (easterly), as they are on Earth, whereas Jupiter and Saturn have prograde winds (westerly) at the equator. [Showman J. Atmos. Sci. 64, 3132- (2007)]

36. Experiments with deep spheres give prograde winds at the equator (red in the right image). The prograde region is outside the cylinder that is tangent to the inner boundary. This tangent cylinder is at the equator in the thin shell models, so the prograde flow does not exist in the thin shell models. [Christensen Geophys. Res. Lett. 28, 2553-2556 (2001)]

37. Another example of prograde flow in a deep sphere model [Heimpel and Aurnou Icarus 187, 540-557 (2007)]. The dashed lines are where the tangent cylinder intersects the surface.

38. Recently two groups have obtained prograde flow in thin shell models by changing the dissipation. This model is by Scott and Polvani (2008, submitted to Geophys Res. Lett.). This is a shallow water model (one layer of fluid) with prescribed random small-scale turbulence. They get prograde equatorial flow by damping the height field ($1/\tau_{rad} > 0$) but not damping the divergence or vorticity fields ($1/\tau_{fr} = 0$).

39. Here is divergence of the eddy momentum flux, showing it is into the jets, in agreement with the observations of $\overline{u'v'}$ and $\partial u/\partial y$. [Scott and Polvani]

40. This is from a 3D model of Schneider and Liu [J. Atmos. Sci, 2008, in press]. Convection of internal heat generates Rossby waves at the equator, which propagate to higher latitudes, where they are damped. This damping is zero outside (equatorward) of the tangent cylinder, and it is large on the poleward side of the tangent cylinder. Except for this change in the damping, the model is a thin shell model.

41. Another difference between the models and the observations. The northward gradient of absolute vorticity $\beta - u_{yy}$ is always positive in the models but it changes sign in the data. This figure shows parabolas $\beta = u_{yy}$ at each of the westward jets. In many cases the curvature of the u profile is greater than the curvature of the parabolas. In a barotropic fluid, $\beta - u_{yy}$ changing sign is a necessary condition for instability. In shallow water models the observed profiles are unstable. Perhaps 3D effects are making them stable, but even the 3D models do not have $\beta - u_{yy}$ changing sign.

42. Now let's talk about vortices. This is the Great Red Spot in red, blue and methane filters. It is a southern hemisphere anticyclone and was discovered in the 1600's soon after the telescope was invented. Small spots go around the periphery in ~10 days. The wind speeds are greater than 100 m/s. The size is 10,000 x 20,000 km, but it has been shrinking for the past few decades. We measure the winds by tracking clouds over 10 hours.

43. Here is a 60-day movie taken by Voyager showing spots merging with the Red Spot. The direction of circulation is counterclockwise, since it is a southern hemisphere anticyclone. Some spots go around and other spots escape. The movie also shows merging of small anticyclones (clockwise rotation) in the northern hemisphere.

44. This is a movie by Dowling and Ingersoll [J. Atmos. Sci 46, 3256 (1989)] of an unstable flow evolving into a series of vortices that merge until there is only one vortex in each latitude band. This unstable flow is taken from observation, so it has $\beta - u_{yy} < 0$ at the centers of the westward jets. The final flow is weaker than the observations, but it is stable.

45. Here is a figure from Dowling and Ingersoll. The final flow does not agree with the observations – it is too weak. This is a problem. The experiments with forced turbulence do not give $\beta - u_{yy} < 0$, and they do not give large ovals. The experiments with large ovals either require creating the ovals with an initial condition or else they require $\beta - u_{yy} < 0$ as the initial condition.

46. The observations show many examples of merging. That raises the question of where do the spots come from?

47. Sometimes they look like convective spots that arise in the belts, which tend to be more turbulent than the zones. [Li etal. Icarus 172, 9-23 (2004)]

48. In 1979 there were three white ovals in an anticyclonic band south of the Red Spot. The ovals are anticyclones, like the Red Spot, and they formed in 1938-1939. You can see two of them in this image. Each oval has a turbulent region to the west and slightly to the north. The turbulent regions are cyclonic, like the turbulent region to the north and west of the Red Spot. They also have the lightning storms.

49. Here is the view in 1998. Two of the large white ovals are close together. The smaller white oval to the south is in a different band. The cyclonic region between the two large ovals is much smaller than it was, and soon it disappeared. The two ovals merged soon after that. The remaining two ovals merged a year later, and now there is only one oval in that latitude band. It recently turned red.

50. Here is a south polar mosaic from Cassini. The remaining white oval is in the 4 o'clock position. Notice the string of ~7 anticyclonic white ovals further to the south. Notice the turbulent cyclonic regions to the north of each of the ovals.

51. Yousef and Marcus [Icarus 162, 74-93 (2003)] have modeled the anticyclonic white ovals and the cyclonic turbulent regions to the north and west of each oval as a Karman vortex street. In this simulation, two ovals of the same sign of vorticity (dark) are orbiting with an opposite vorticity spot (white) that keeps them from interacting. Another white spot approches the triplet and knocks the white spot away. The remaining black spots quickly merge, implying that the cyclonic spot was keeping the two white ovals apart.