Simulations of the Great Dark Spots of Neptune and Uranus

Xiaolong Deng, Raymond P. LeBeau, Jr.
Department of Mechanical Engineering
University of Kentucky

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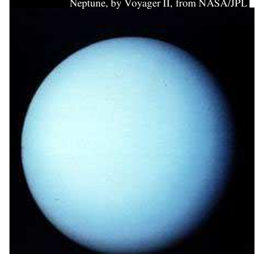
Uranus and Neptune

- Seventh and eighth planets of solar system.
- Similar size: ~2.5×10^4 km
- Similar structure: gas giant planets.
- Similar atmosphere components: Hydrogen, Helium, Methane
- Similar pressure-temperature profiles

Key Interesting Differences

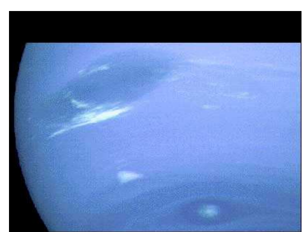
- Heat source: for Neptune, internal source is most important; for Uranus, solar radiation is dominant.
- Obliquity: Uranus has the unique extreme obliquity (98°) in our solar system, which leads to special seasonal changes. Uranus is approaching its equinox on Dec. 7, 2007. This obliquity also leads to a north pole direction below the plane of revolution.
- Dynamics: Neptune was much more dynamic than Uranus.


Neptune, by Voyager II, from NASA/JPL


Uranus, by Voyager II, from NASA/JPL

Great Dark Spot (GDS)

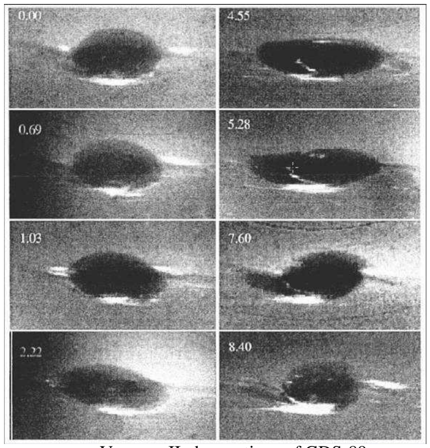
- A kind of roughly elliptical region in the planetary atmosphere with darker albedo.
- Physically, they are big vortex features
- GDS-89 on Neptune – dynamics
- Another large vortex: Great Red Spots (GRS) on Jupiter – long-lived


GDS, Scooter & Small Dark Spot, from NASA/JPL


Great Red Spot on Jupiter, from NASA/JPL

GDS-89 on Neptune

- 1989, Voyager II
- Size: ~38° in longitude, ~14° in latitude
- Position: 27° to 17° in the southern hemisphere
- Life time: several years
- Oscillation: 8-day (193-hour) period oscillation in shape (aspect ratio, tail)
- Drift: 1.24°/month drift to equator
- Bright companion: methane cloud



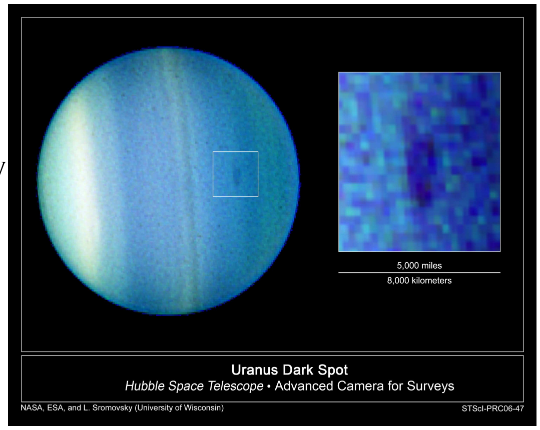
Voyager II observations of GDS-89.
From Stratman et al. 2001.

Other GDSs on Neptune

- GDS-89 on Neptune was not unique
- NGDS-32: found by HST in 1994, bright companion, ~32° in northern hemisphere, size 34° in longitude by 12° in latitude, drift? Disappeared before 1998?
- NGDS-15: found by HST in 1996, no bright companion, much smaller, drift?

Dark Spot on Uranus

- The first observed vortex feature on Uranus was found on Aug. 23, 2006
- Size: 1,100 miles by 1,900 miles (1,700 km by 3,000 km)
- Position: ~27° in the northern hemisphere
- Life time: >1 day (observed on Aug. 23 & Aug. 24)
- Related to the seasonal change?



EPIC Model

- Explicit Planetary Isentropic Coordinate, presented by T. Dowling et al. in 1998.
- General Circulation Model (GCM)
- Three dimensional, run in parallel
- EPIC uses a hybrid vertical coordinate, ζ, that transits continuously from θ aloft to a terrain following coordinate σ .

Hybrid coordinate ζ in EPIC

Sigma-theta vertical c'oordinate Terrain following near surface Isentropic coordinate aloft

$$\zeta = \tilde{f}(\sigma) + \tilde{g}(\sigma)\theta.$$

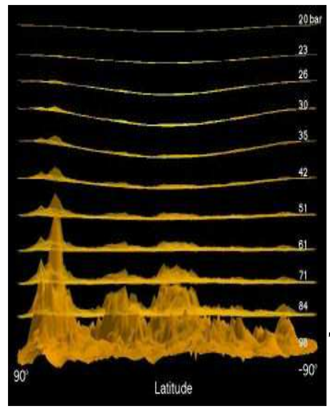
$$\sigma \equiv \frac{\log(p/p_{bot})}{\log(p_{top}/p_{bot})},$$

Top: $g = 1$, $f = 0$ and $\zeta = \theta$

Bottom: $g = 0$, $f = f(0)$, $\zeta = f(\sigma) = f(0)$

Vertical velocity

$$\dot{\zeta} = \frac{\partial F}{\partial \theta}\dot{\theta} + \frac{\partial F}{\partial p}\dot{p} + \frac{\partial F}{\partial p_{bot}}\dot{p}_{bot}$$



Potential temperature

Topography

Governing Equations

Formulation of Konor and Arakawa (MWR, 1997)

$$\left.\frac{\partial h}{\partial t}\right|_{\zeta} + \left.\frac{\partial}{\partial x_j}(hu_j)\right|_{\zeta} + \frac{\partial}{\partial \zeta}(h\dot{\zeta}) = 0, \quad h \equiv -\frac{\partial p}{\partial \zeta}$$

$$\left.\frac{\partial u_i}{\partial t}\right|_{\zeta} + u_j \left.\frac{\partial u_i}{\partial x_j}\right|_{\zeta} + \dot{\zeta}\frac{\partial u_i}{\partial \zeta} = -\left.\frac{\partial M}{\partial x_i}\right|_{\zeta} + c_p\left(\frac{p}{p_0}\right)^{\kappa}\left.\frac{\partial \Phi}{\partial x_i}\right|_{\zeta} - f\hat{k}\times u_i - \frac{\partial(\overline{u_i' u_j'})}{\partial x_j}$$

$$\left.\frac{\partial \theta}{\partial t}\right|_{\zeta} + u_j \left.\frac{\partial \theta}{\partial x_j}\right|_{\zeta} + \dot{\zeta}\frac{\partial \theta}{\partial \zeta} = \frac{Q}{\Pi} - \frac{\partial(\overline{\theta' u_j'})}{\partial x_j}, \quad \theta = \left(\frac{p_0}{p}\right)^{\kappa} T = \frac{c_p T}{\Pi}$$

$M = c_p T + \Phi$, Montgomery potential

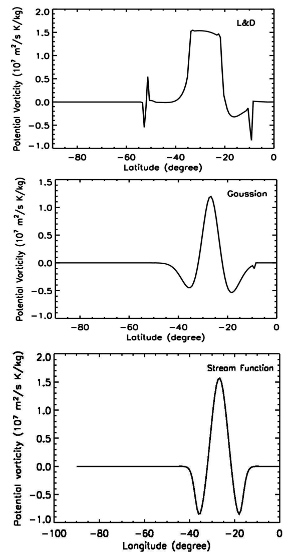
ζ = Hybrid vertical coordinate

f = Coriolis parameter

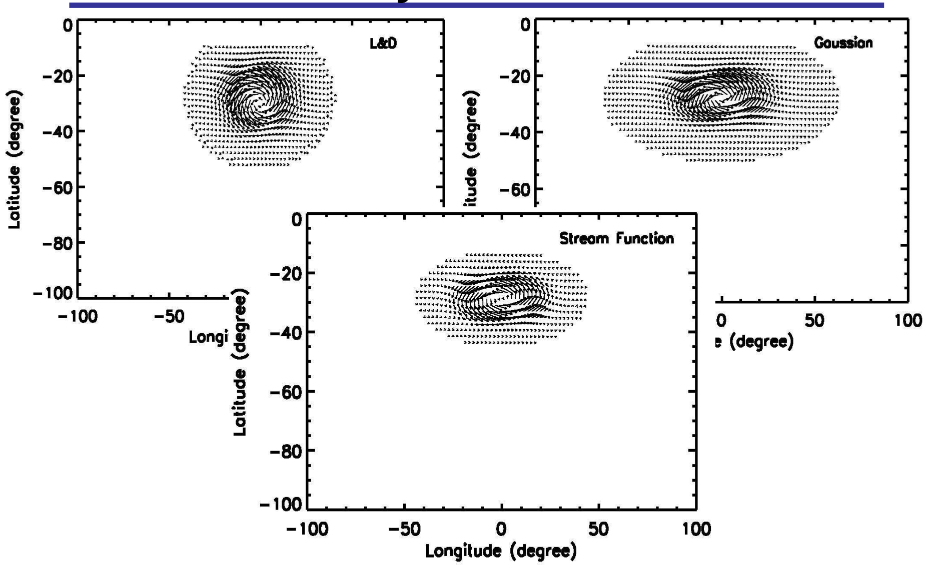
Π = Exner function $= c_p (p_0/p)^{\kappa} = c_p (T/\theta)$

Vortex Generation in EPIC

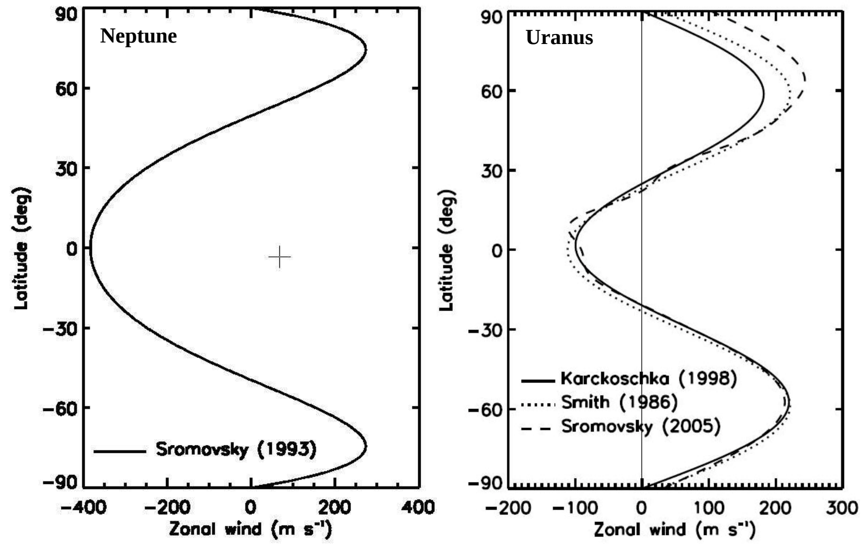
- Perturbing the Montgomery potential
  - Near flat, LeBeau & Dowling 1998
  - Gaussian shape, Stratman et al. 2001
- Stream function – new spot maker (Herrenstein & Dowling)



Velocity Distribution



Wind Profiles



Artificial Wind Profiles

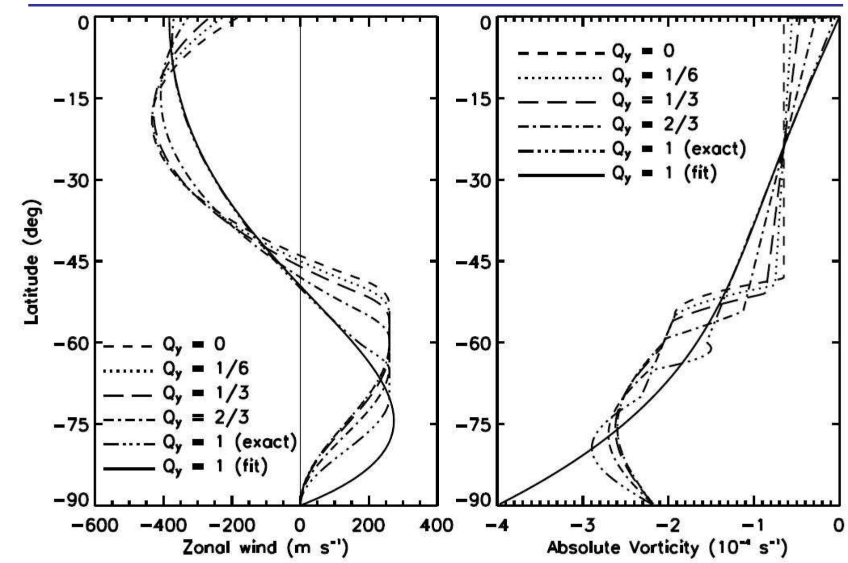
- Modify the absolute vorticity balance equation:

$$-\frac{1}{rR}\frac{\partial(ur)}{\partial\lambda} + f = (\omega + f)_0 + Q_y\beta^* R_0(\lambda - \lambda_0), \beta^* \equiv \left[\frac{1}{R}\frac{\partial}{\partial\lambda}(\omega + f)\right]_{\lambda=\lambda_0}$$

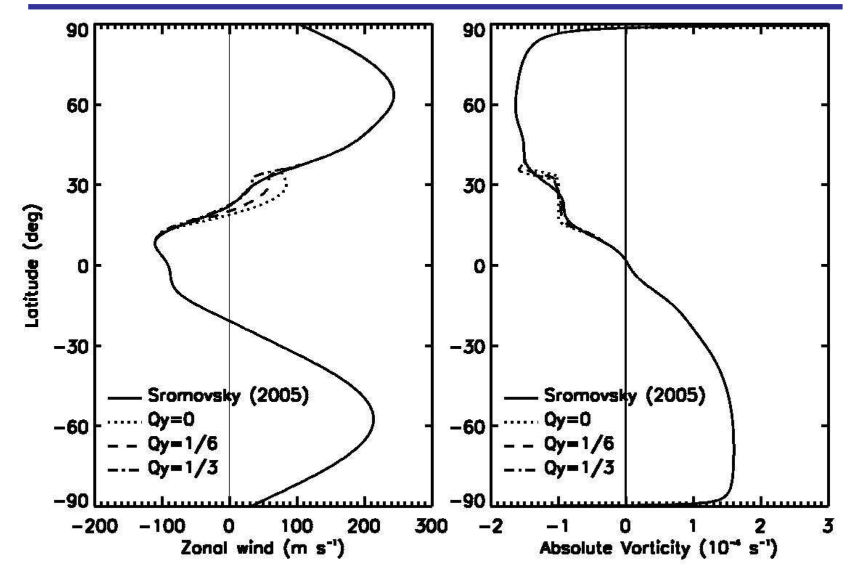
  f = 2Ωsin λ is Coriolis force, ω=-1/(rR)*(∂(ur)/∂λ).

- For Neptune, ref. latitude λ_0=-24°, based on the Sromovsky et al. 1993 profile, from the mid-latitude to the equator.
- For Uranus, λ_0=27°, based on the Sromovsky et al. 2005 profile, from N22° to N32°.

Artificial Wind Profiles – Neptune



Artificial Wind Profiles – Uranus



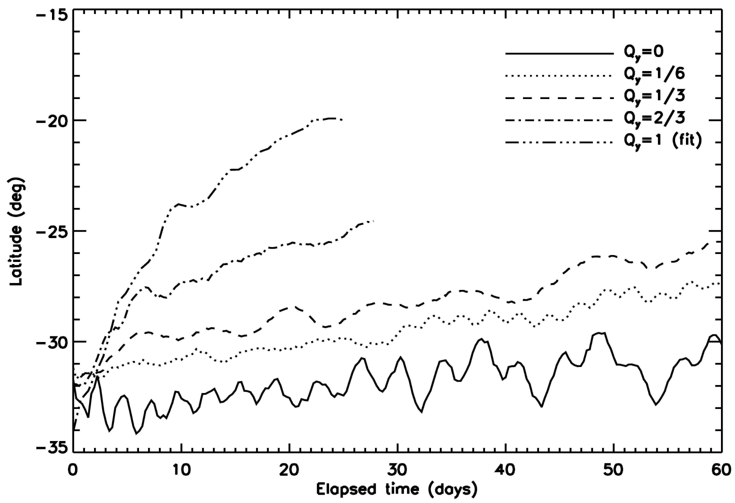
Computer Resource – KFC6I

- Operational December 2006
- Currently housed at UK CFD
- 1 processor per node
- 23 nodes + 1 server
- CPU: 2.13Ghz Intel e6400 Core 2 Duo 64bit, 2MB Shared L2 Cache
- RAM: 1GB per node, 2GB on server
- Single-48 port Gigabit Switch Network

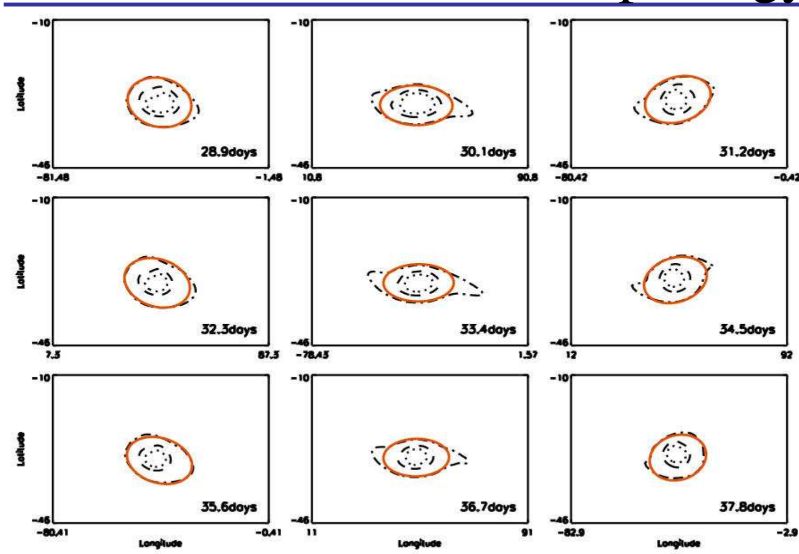
Simulation Results -- Focuses

- Neptune's GDS89 – Dynamics:
  - Drift rate
  - Morphology (shape, tail formation)
  - Oscillation (aspect ratio of the ellipse, phase angle)
- Uranian Dark Spot – Sustainability:
  - Which latitude is most suitable for a vortex to survive in the atmosphere
  - Which kind of wind profile is the best to sustain a vortex

Result for GDS89 – Drift Rate

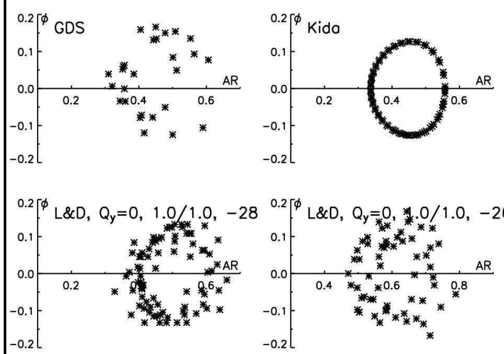


Results for GDS89 – Morphology

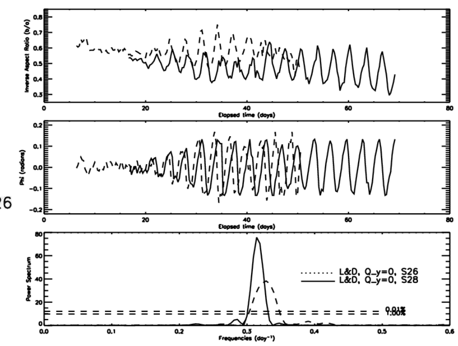


Results for GDS89 – Oscillation

Angle (ϕ) vs. Aspect Ratio (AR)



ϕ (up) and AR (middle) vs. time



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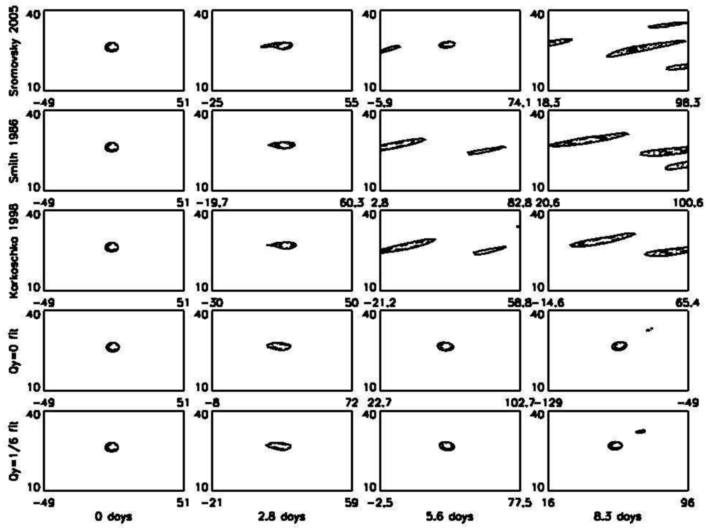
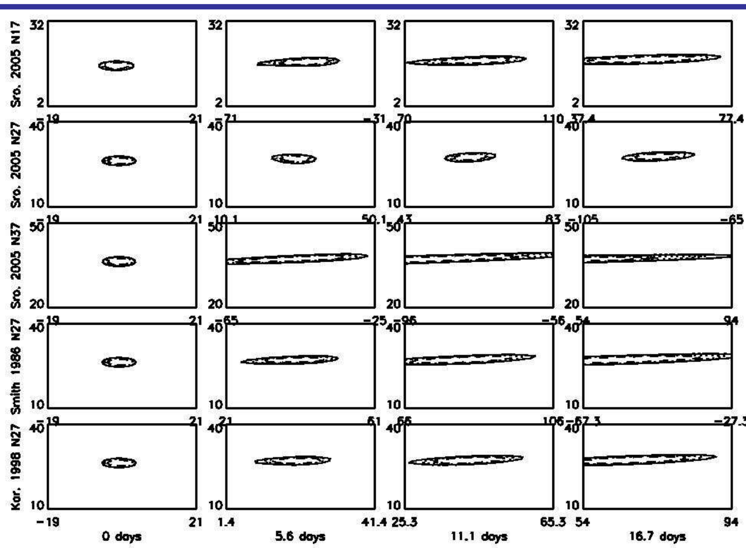
Q_y	l_0	Rel. Str./Size/Initial AR	Drift(°/m)	Period(days)	Inverse AR	Phi(rad)
GDS-89 at -18°S			1.24	8.0	0.42±0.12	0±0.15
GDS-89 at -22°S			1.24	8.0	0.35±0.11	-
0	26° S	1.0/1.0/1.5	1.0	3.0	0.59±0.14	0±0.17
0*	26° S	1.0/1.0/1.0	-2.3	3.0	0.41±0.16	0±0.13
0*	26° S	1.0/1.0/1.7	-0.7	2.9	0.69±0.13	0±0.18
0	28° S	1.0/1.0/1.5	1.3	3.1	0.51±0.16	0±0.16
0	28° S	1.0/1.0/0.8	1.3	3.3	0.31±0.11	0±0.13
0	28° S	1.0/1.0/3.0	2.8	0.8	0.72±0.22	0±0.13
0	28° S	0.7/1.0/1.5	1.3	3.2	0.33±0.21	0±0.13
0*	28° S	1.0/1.0/1.5	0.9	3.2	0.48±0.14	0±0.13
0*	28° S	1.2/1.1/1.5	0.3	3.1	0.58±0.13	0±0.14
0	28° S	1.5/1.3/1.5	1.4	3.1	0.49±0.27	0±0.14
0	28° S	2.0/1.3/1.5	3.3	1.4	0.81±0.20	0±0.15
0*	28° S	2.0/1.3/1.5	0.5	1.7	0.75±0.25	0±0.13
0	30° S	1.0/1.0/1.5	0.7	3.1	0.49±0.14	0±0.17
0	32° S	1.0/1.0/1.5	1.2	3.6	0.40±0.15	0±0.14
0	32° N	1.0/1.0/1.5	-1.2	3.6	0.40±0.15	0±0.14
0	32° S	2.0/1.3/1.5	0.5	3.9	0.45±0.07	0±0.08
0	34° S	1.0/1.0/1.5	-0.8	4.3	0.36±0.13	0±0.13
0	34° S	2.0/1.3/1.5	-0.1	4.8	0.38±0.02	0±0.03
1/6	32° S	1.0/1.0/1.5	2.1	2.7	0.38±0.04	0±0.05
1/6	34° S	1.5/1.3/1.5	1.1	2.8	0.33±0.07	0±0.05
1/3	32° S	1.0/1.0/1.5	3.8	7.7	0.39±0.05	0±0.03
1/3	36° S	1.5/1.3/1.5	0.3	4.2	0.33±0.02	0±0.02

Uranus – effect of absolute vorticity



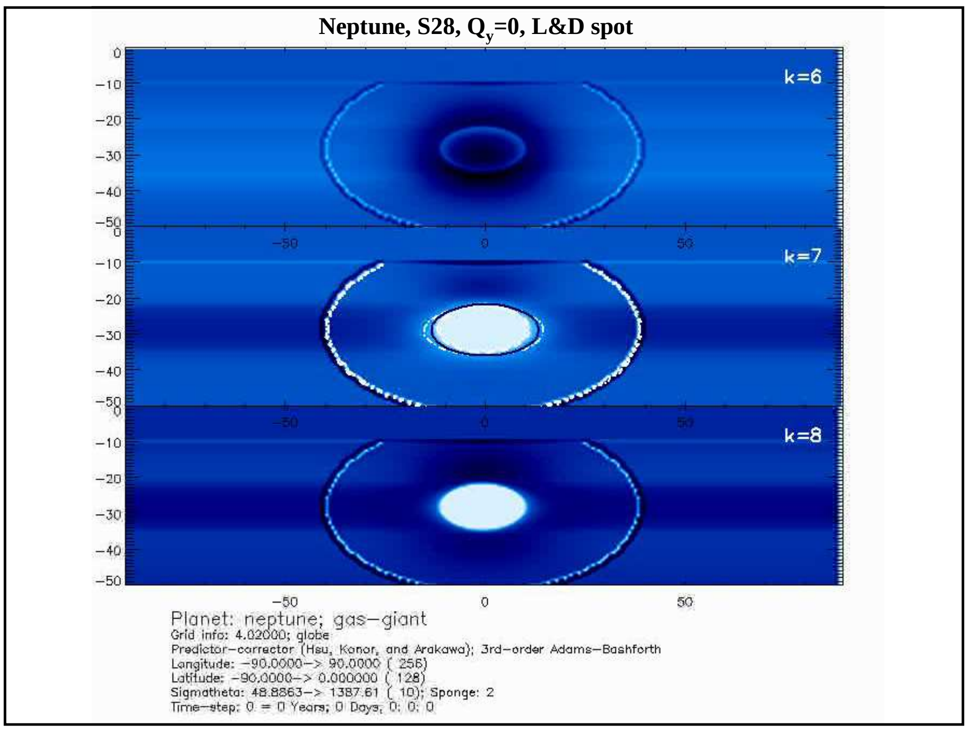
Parameters: pressure=500mbar, amplitude=30m/s, N27 °

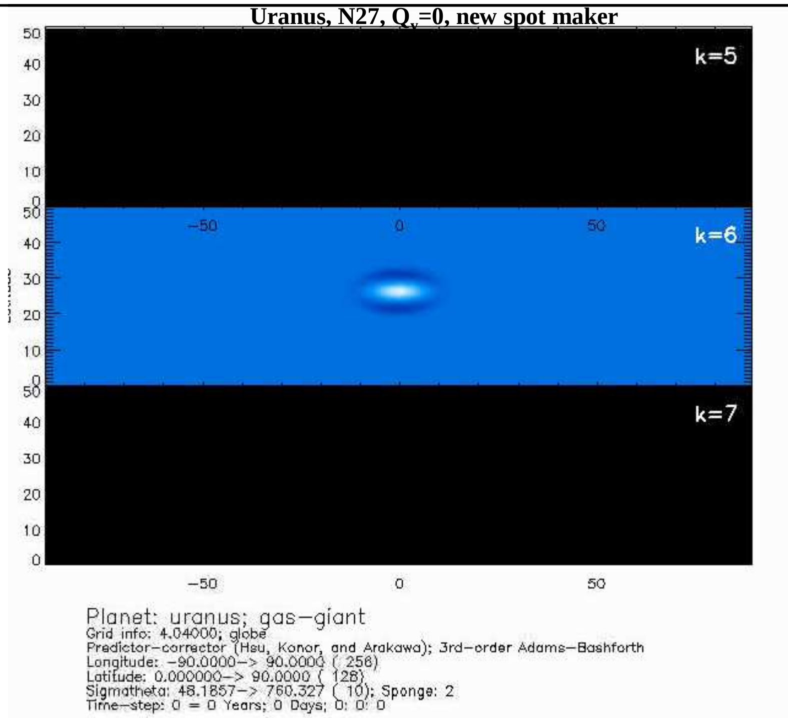
Stronger spots and Latitude effect



Parameter: pressure=500mbar, amplitude=70m/s

zonal wind	Amp. (m/s)	Lat. (°)	life (day)	range	drift
Sromovsky	50	27	26	Equator to North Pole	
Sromovsky	70	7	14	Equator to North Pole	to north pole
Sromovsky	70	17	15	Equator to North Pole	to north pole
Sromovsky	70	22	22	Equator to North Pole	a little, to north pole
Sromovsky	70	27	31	Equator to North Pole	
Sromovsky	70	32	10	Equator to North Pole	
Sromovsky	70	37	5	Equator to North Pole	
Sromovsky	70	47	10	Equator to North Pole	
Sromovsky	70	65	8	Equator to North Pole	
Sromovsky	70	75	3	Equator to North Pole	
Smith	70	27	13	Equator to North Pole	
Karkoschka	70	27	17	Equator to North Pole	
Qy=0	30	27	>70	Equator to North Pole	
Qy=0	50	27	>70	Equator to North Pole	
Qy=0	70	27	>70	Equator to North Pole	
Qy=0	70	27	>70	Pole to Pole	
Qy=0	90	27	>70	Equator to North Pole	
Qy=1/6	30	27	45	Equator to North Pole	
Qy=1/6	50	27	50	Equator to North Pole	
Qy=1/6	70	27	55	Equator to North Pole	
Qy=1/6	90	27	61	Equator to North Pole	
Qy=1/3	30	27	12	Equator to North Pole	
Qy=1/3	50	27	10	Equator to North Pole	
Qy=1/3	70	27	6	Equator to North Pole	





Conclusion

Neptune

- Drift: to equator, the best fit is Q_y=0
- Oscillation: most with ~3-4 day period, tail formation
- Life time: can be very long
- Induced waves

Uranus

- Drift: at low latitude, drift to pole
- Oscillation: yes
- Life time: Q_y=0 gives the best result (>70 days), bigger Q_y => less life
- Can induce new spots

Further work: Radiation-Convection model, Cloud model.

Thank you!

Questions?