Computational Fluid Dynamics Simulations of the Great Dark Spots of Neptune

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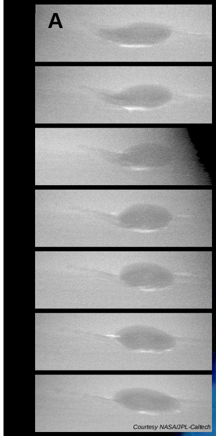
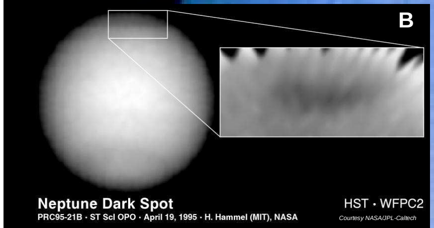
The Changing Atmosphere of Neptune



Courtesy NASA/JPL-Caltech

The Voyager II encounter with Neptune revealed a number of atmospheric features that now form the standard vision of Neptune (as well as the background of this poster). Most prominent was the Great Dark Spot (GDS-89), a probable vortex feature with angular dimensions comparable to the Great Red Spot of Jupiter. But the GDS was much more dynamic than the large Jovian vortices, with an 8-day (193 hour) periodic oscillation in shape and evolving average dimensions (**A**). GDS-89 was observed to travel from -27^{o}S to -17^{o}S latitude during the encounter, a 1.24^o/month latitudinal drift towards the equator. A second possible vortex feature, D2, was observed around 50^{o}S latitude. Bright methane cloud features include the Bright Companion cloud that accompanied GDS-89 and the triangular Scooter. However, this image of Neptune is apparently ephemeral—Hubble Space Telescope (HST) observations in 1992 failed to spot GDS-89, while later observations (1994-1996) revealed two new spots, NGDS-32 (**B**) and NGDS-15. But again, by 1998 neither of these dark features were observable, and the overall atmospheric picture had changed again (**C**). These dynamic features present both challenging flow physics problems and a unique opportunity to validate planetary atmospheric models against well-defined numerical data.

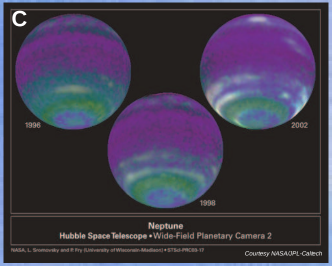


Neptune Dark Spot

HST • WFPC2

PRC95-21B • ST Scl OPO • April 19, 1995 • H. Hammel (MIT), NASA

Courtesy NASA/JPL-Caltech



Neptune
Hubble Space Telescope • Wide-Field Planetary Camera 2

NASA, L. Sromovsky and P. Fry (University of Wisconsin-Madison) • STScI-PRC03-17

Courtesy NASA/JPL-Caltech

Numerical Model and Methodology

The numerical simulations are conducted with the Explicit Planetary Isentropic Coordinate General Circulation Model (EPIC GCM). The basic equations solved are a modified form of the Navier-Stokes equations with a hybrid vertical coordinate (**D**) applied to a series of stacked fluid layers. The hybrid coordinate is designed to allow use of a flow-following potential temperature coordinate (θ) aloft and a pressure-based coordinate (σ) as a solid surface is approached (**E**). For a gas giant, the hybrid coordinate allows for finer vertical spacing in the near-isothermal troposphere where potential temperature is nearly constant. Current simulations typically involve a quarter globe from the south pole to the equator and 180^o in longitude (periodic boundary) on a grid of 256x128 horizontal points (spacing of 0.7^o) and 10-13 vertical layers with a timestep on the order of one minute.

D

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

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

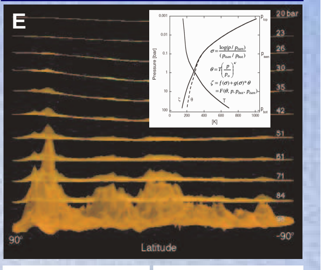
$$\left.\frac{\partial \theta}{\partial t}\right|_{\zeta} + u_j\left.\frac{\partial \theta}{\partial x_j}\right|_{\zeta} + \dot{\zeta}\frac{\partial \theta}{\partial \zeta} = \frac{Q}{\Pi} - \frac{\partial(\overline{\theta' u_j'})}{\partial x_j}, \quad \theta = \left(\frac{p_0}{p}\right)^{\kappa} T =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

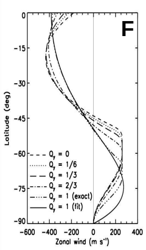
$M = c_p T + \Phi =$ Montgomery potential, $\zeta =$ Hybrid vertical coordinate

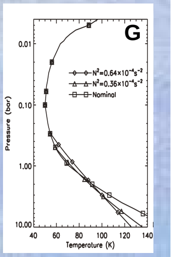
$f = 2\Omega \sin\lambda =$ Coriolis parameter, $\Pi = c_p (p_0/p)^{\kappa} =$ Exner function

The key model parameters used to investigate this system are integrated into the process of initialization. The atmospheric model requires input of a zonal wind structure and vertical temperature-pressure profile. The horizontal zonal winds on the jovian planets have proved notably stable, but the cloud tracking data does leave some flexibility in the final form. The zonal wind patterns chosen are variations on the latitude fit of Sromovsky *et al.* (1993) (**F**, "Q_y = 1 (fit)"), modified to decrease the local potential vorticity gradient to a fraction of the Sromovsky *et al.* profile. The profile of temperature and pressure is also based on observations (**G**, "Nominal"), but in the not well-observed or constrained deeper regions other profiles are constructed to investigate varying the buoyancy frequency (N).

The other critical parameters are part of the vortex induction process – the model Dark Spot is induced by locally deflecting the Montgomery potential in the manner of LeBeau and Dowling (1998) or Stratman *et al.* (2001) and then geostrophically corrected the velocity fields. This correction created nearly-balanced spots in a pure isentropic model, but in the hybrid coordinate version the spot must adjust over the first 5-10 days of the simulation before achieving its long-term, balanced configuration. The spot then continues to evolve and its resulting motions and properties are compared to the available observational data.

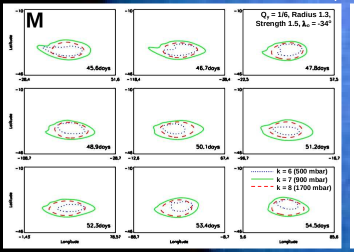


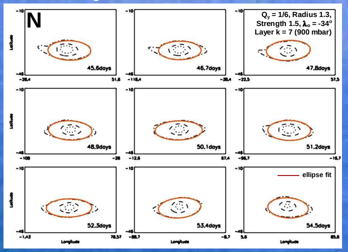


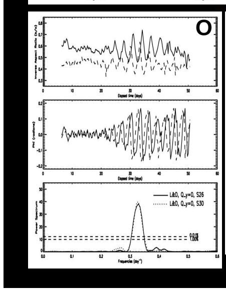


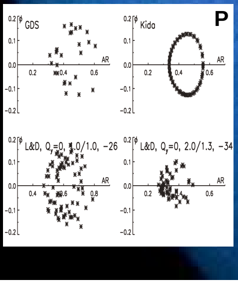
GDS Morphology

The characteristic morphology of the GDS was of an ellipse oscillating in both aspect ratio and angle of orientation (ϕ) measured between the major axis and the horizontal. The aspect ratio and orientation angle oscillations were 90^o out-of-phase, with the maximum and minimum aspect ratio occurring when ϕ ~ 0^o. Also on the same 8-day period the ellipse exhibited "tails" or a tadpole-like shape (**A**), with the more prominent tails to the west of the vortex. As the GDS drifted towards the equator, the mean aspect ratio changed as the average vertical angular dimension increased by about a 0.8^o/degree latitude, with an average size of 14^o during the best two months of observation. The mean horizontal angular dimension was nearly constant at 38^o degrees. The EPIC vortices, defined by closed contours of potential vorticity which closely approximates a material boundary, have captured all these characteristics qualitatively. Multi-layer shape oscillations (**M**) and tail formations (**N**) have been simulated with an oscillation period of days (**O**). The basic phase relationship between the aspect ratio and orientation angle also is commonly achieved (**P**), as has the trend of aspect ratio growth with latitude (**Q**). Current work is to achieve quantitative matches, as no single spot has yet captured all the features of GDS-89. Note that all the results shown here are L&D vortices, which tend to produce stronger oscillations.





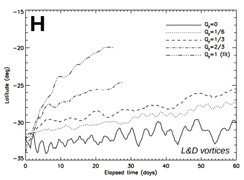


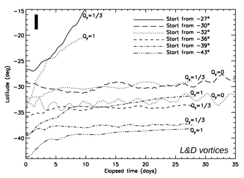


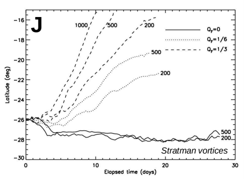
Q Q_y	λ_0	Rel. Str./ Size	Drift (°/m)	Period (days)	AR	Phi (rad)
GDS-89 at -18°S			1.24	8.0	0.42±0.12	0±0.15
GDS-89 at -22°S			1.24	8.0	0.35±0.11	-
0	26° S	1.0/1.0	1.0	3.0	0.59±0.14	0±0.17
0	30° S	1.0/1.0	0.7	3.1	0.49±0.14	0±0.17
0	32° S	1.0/1.0	1.2	3.6	0.40±0.15	0±0.14
0	32° S	2.0/1.3	0.5	3.9	0.45±0.07	0±0.08
0	34° S	1.0/1.0	-0.8	4.3	0.36±0.13	0±0.13
0	34° S	2.0/1.3	-0.1	4.8	0.38±0.02	0±0.03
1/6	32° S	1.0/1.0	2.1	2.7	0.38±0.04	0±0.05
1/6	34° S	1.5/1.3	1.1	2.8	0.33±0.07	0±0.05
1/3	32° S	1.0/1.0	3.8	7.7	0.39±0.05	0±0.03
1/3	36° S	1.5/1.3	0.3	4.2	0.33±0.02	0±0.02

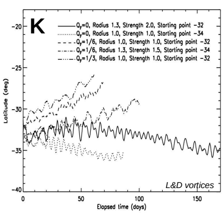
GDS Drift

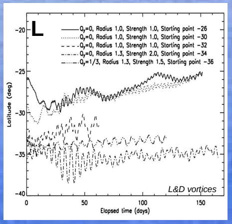
The mean drift rate of 1.24^o/month for GDS-89 was observed to be essentially constant over an 8 month period, although the geometric center showed additional variations due to the shape oscillations. To date, the drift rate has been strongly dependent on the background potential vorticity gradient (**H**), the vortex latitude (**I**), and to a lesser extent the vortex structure (**H,J,K,L**). At mid-lattiudes (below 30^{o}S) long-term drift rates on the order of a degree/month can be achieved for all potential vorticity gradients tested, but at more equatorward latitudes only profiles with smaller Q_y have been able to maintain moderate drifts (**I**). Thus, recent simulations have targeted zonal wind profiles with Q_y = 0, 1/6, and 1/3 (**K,L**). Some of these simulations have maintained steady drift rates over several months of simulated time.











Conclusions

The current results suggest that GDS-89 needed a low background potential vorticity gradient to maintain its observed drift rate from latitudes of 27^{o}S to 17^{o}S. This may reflect the actual zonal wind profile, or a GDS-induced local and temporary mixing as suggested by Polvani *et al.* (1991). The lack of observed drift by the NGDS suggest that these effects are reflected across the equator. EPIC vortices also exhibit GDS-like shape changes over periods of several days, growth in aspect ratio with higher latitude, and a similar phase pattern as GDS-89 and the Kida vortex. However, exact numerical matches still need to be achieved for single vortex. Overall, the evidence is that the GDS motions do provide a challenging validation target, which could lead to a better validated EPIC GCM. The knowledge gained could then be applied through comparative planetology to the atmospheres of other planets (including Earth) or used to prepare for future missions to Neptune.

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Background image courtesy NASA/JPL-Caltech