Shear driven instabilities and shocks in the atmospheres of hot Jupiters

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Abstract

Strong equatorial eastward jets with supersonic velocities are a common feature of hot Jupiter atmospheric models. Using compressible 3D numerical simulations performed with the code RAMSES (Teyssier 2002), we show that such jets are destabilized by hydrodynamical instabilities associated with the horizontal and vertical zonal velocity shears. We also find signature of weak shocks in the atmosphere upper layers. We discuss the possible consequences of our findings.

Method

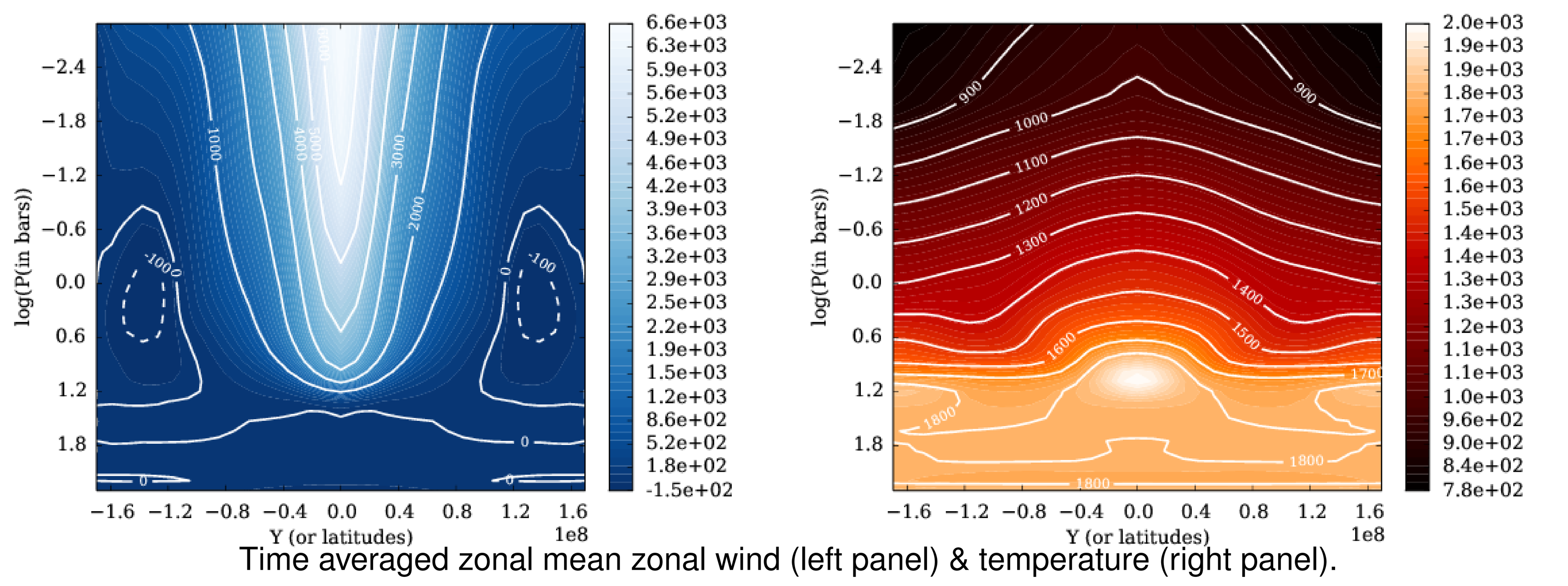
- Solve the compressible Euler hydrodynamic equations using the public code RAMSES (Teyssier 2002).
- Use a Cartesian coordinate system along with the equatorial β-plane approximation.

$$\mathbf{\Omega} = \frac{1}{2}\beta y \mathbf{e_z} \quad (1)$$

- Use Newtonian cooling to mimic gas heating and cooling.
- Vary the spatial resolution: $(N_x, N_y, N_z) = (64, 33, 48)$ (low resolution) and $(N_x, N_y, N_z) = (1024, 195, 48)$ (high resolution).

A benchmark model

- Results of standard benchmark models (e.g. Heng et al. 2011) are reproduced even at low resolution.

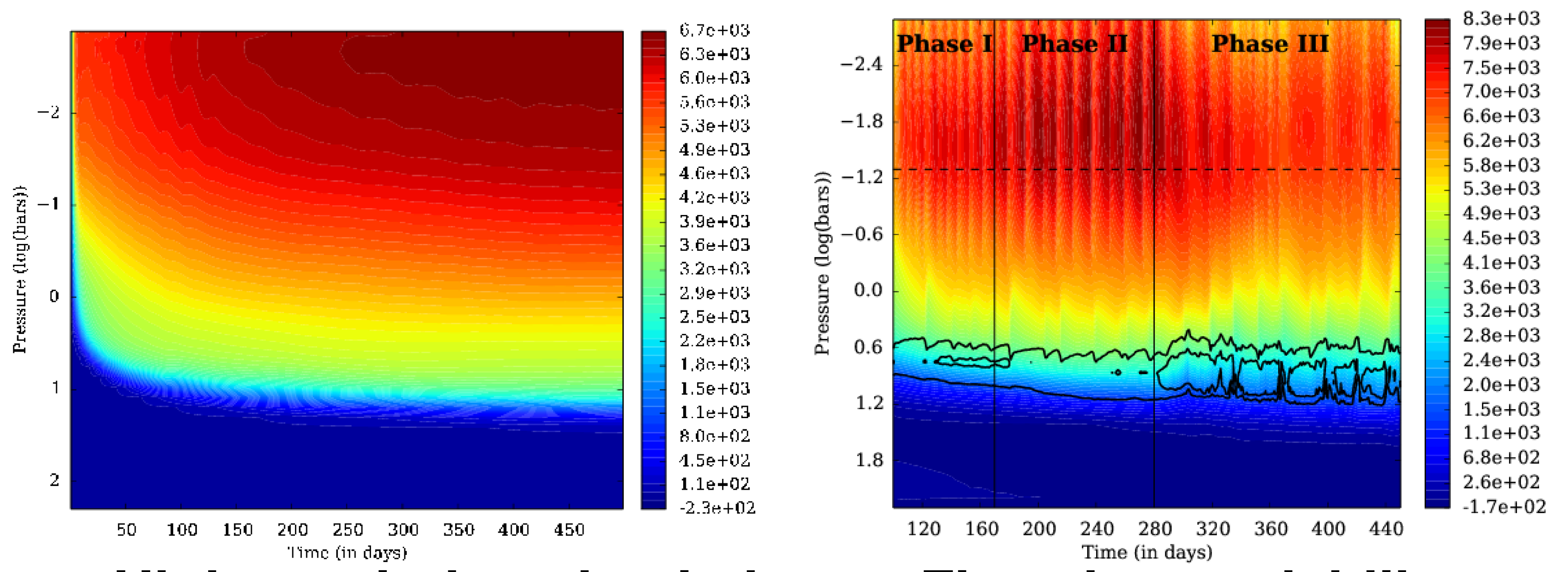


Time averaged zonal mean zonal wind (left panel) & temperature (right panel).

The effect of spatial resolution

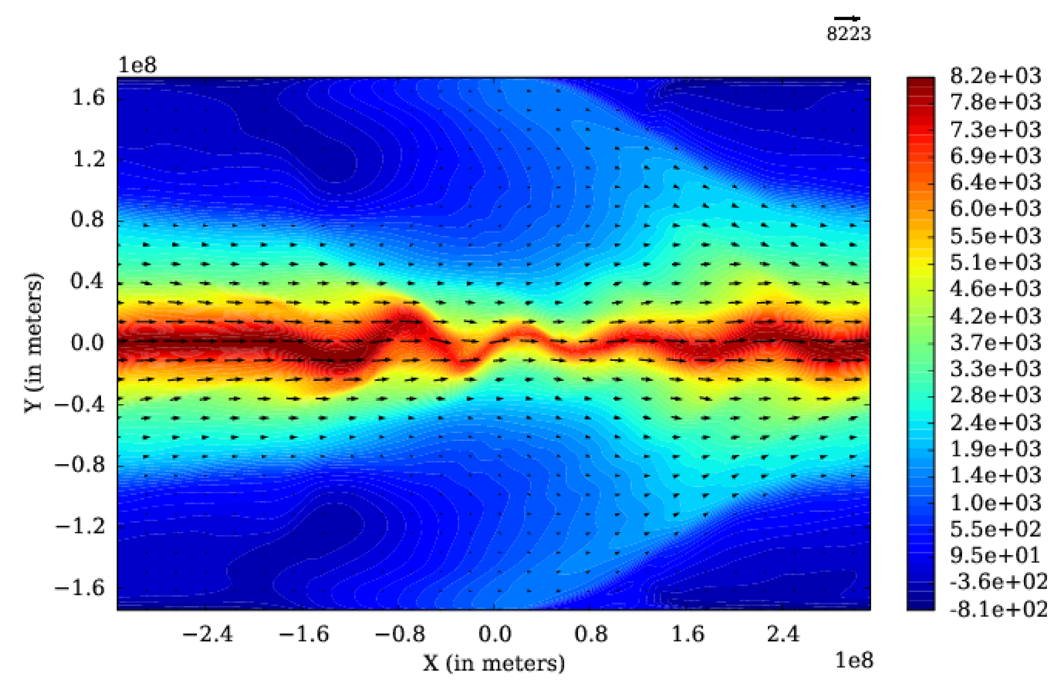
Spacetime diagram of the equatorial zonal velocity

Low resolution *High resolution*



High resolution simulation ⇒ Flow time variability

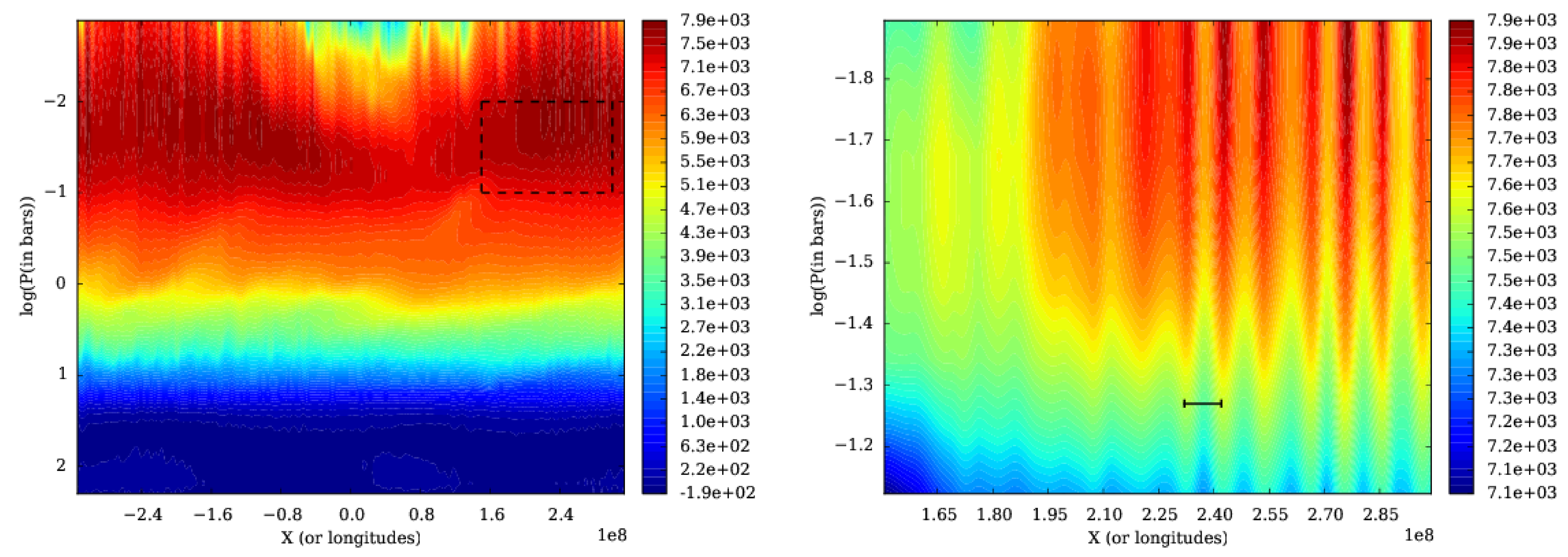
Phase II: A barotropic KH instability



Flow features

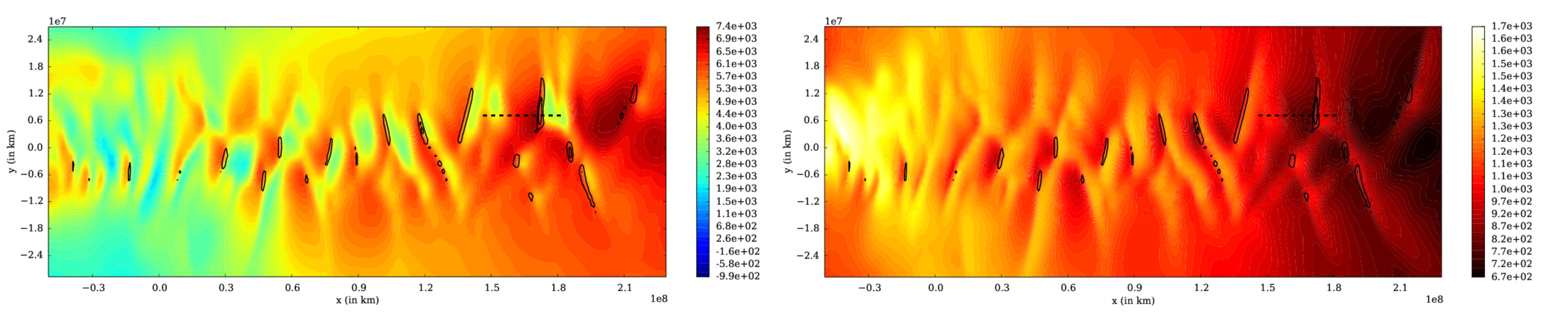
- Quasi-periodic growth and decay of equatorial jet meanders.
- Decent agreement with linear stability analysis.
- Jet slows down when the instability saturates (drag mechanism?).

Phase III: vertical shear instability & shocks



Zonal velocity in a (x,P) plane during Phase III (left panel) and zoom on the dashed box (right panel)

- Small scale fluctuations during Phase III associated with small Richardson numbers (solid contours in spacetime diagram).
- Typical scale ($L \sim 10^4$ km) consistent with linear analysis of the vertical shear instability (Li & Goodman 2010).
- Weak shocks (see below) at mbar pressure levels. Profile consistent with Rankine-Hugoniot jump conditions.



zonal wind (left panel) and temperature (right panel) at the vicinity of the equator during Phase III. Black contour show region of high compression. A shock location is marked by a dashed line.

Conclusions

- Compressible model reproduces GCM benchmark model of hot Jupiter atmospheres in the equatorial β–plane approximation
- High resolution simulations feature an increased time-variability due to a barotropic shear instability in the atmosphere upper-layers ($P \sim$ a few hundreds mbar) and a vertical shear instability in the deeper layer ($P \sim 10$ bar).
- Weak shocks appear only in the atmospheric upper layers ($P \sim 1$ mbar)
- Potential consequences & future work: drag mechanism associated with the instabilities, heat deposition in the atmospheric deep layers (inflated radii of hot Jupiter?), effect of time variability on NIR light curve.

Fromang, Leconte & Heng, 2016, A&A, 591, 144 – sebastien.fromang@cea.fr