Dynamics of nuclear burning during type-I X-ray bursts

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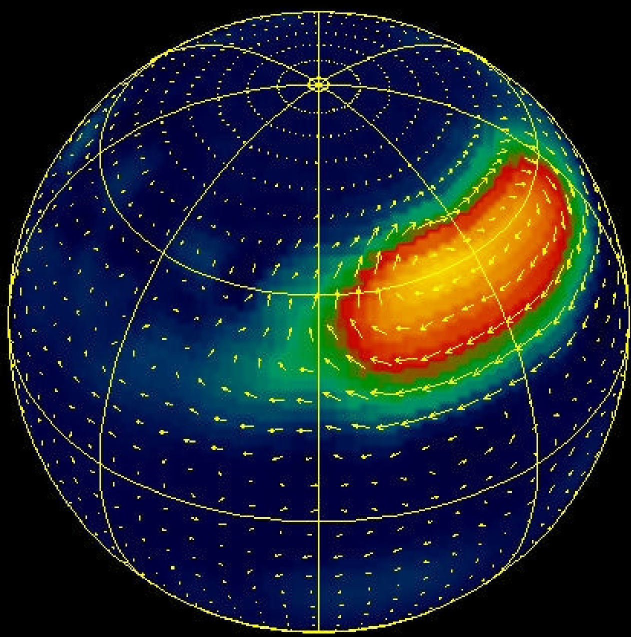


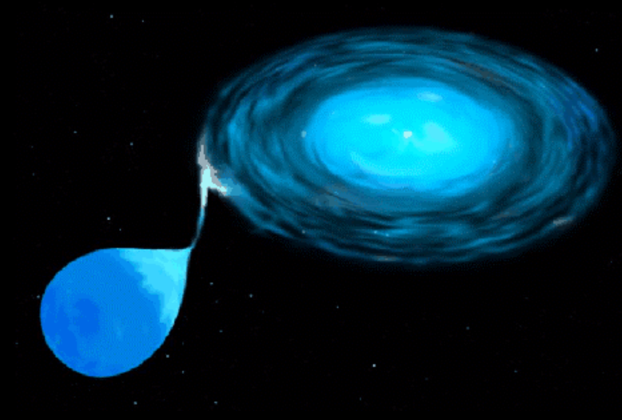
Propagation of thermonuclear flames on rotating neutron stars

1. Overview of X-ray burst phenomena
2. Effects of rotation and structure of burning fronts
3. Propagation of burning on a sphere
4. Burning dynamics in magnetic fields -- application to SAX J1808
5. Conclusions and connection to observations

Collaborators: Greg Ushomirsky (MIT) and Yuri Levin (CITA)

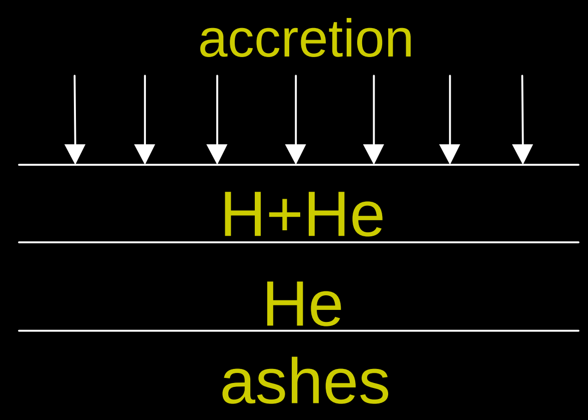
Overview of X-ray bursts

Accreting neutron stars in Low-Mass X-ray binaries



- Companion < 1 M_{sun}; period hours-days; accretion through Roche lobe overflow
- Accretion of H and He, $\dot{M} = 10^{-11} - 10^{-8} M_{sun} \mathrm{yr}^{-1}$
- Bursts: ~50 sources, energy ~10^{39} ergs, duration 10-100s, recurrence hours to days.
- Energy, duration and recurrence can be explained as a thermonuclear flash on the surface. High temperature sensitivity of He burning:

$$\frac{d\,e_{\mathrm{nulc}}}{d\,T} > \frac{d\,e_{\mathrm{cool}}}{d\,T}$$



Thermonuclear bomb!

Overview of X-ray bursts

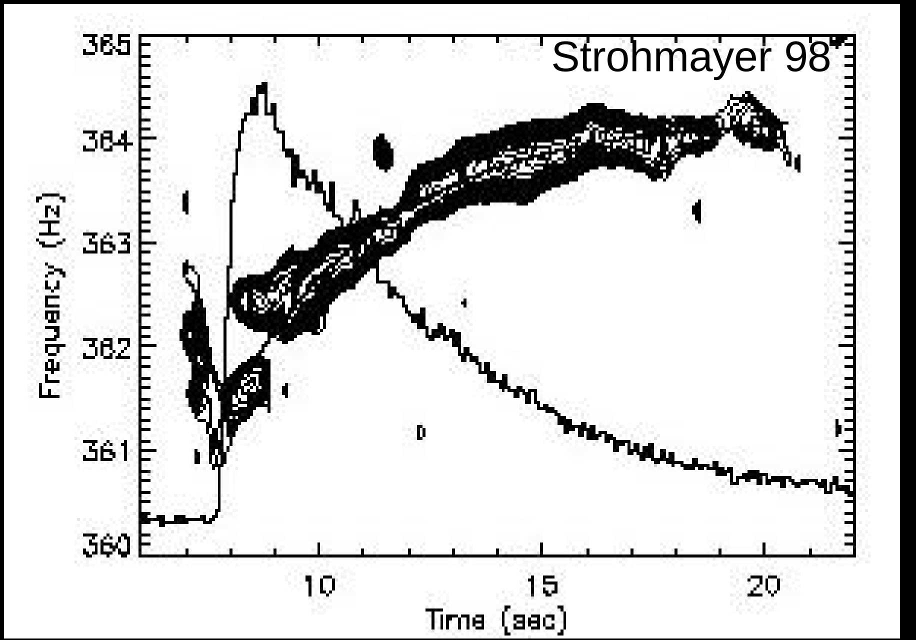
Accreting neutron stars in Low-Mass X-ray binaries

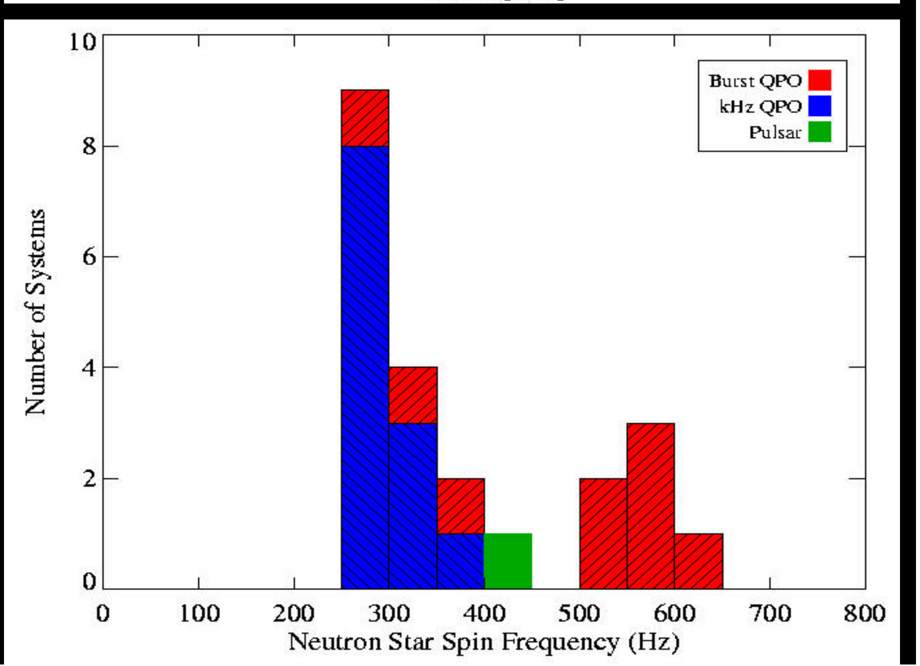
- Expect these NS to rotate rapidly:

$$\frac{dJ}{dt} = (GMR)^{1/2}\dot{M}$$

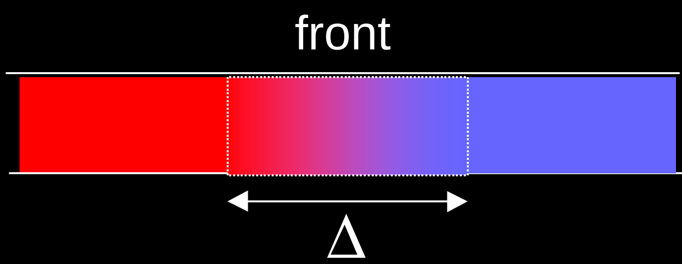
Favored progenitors of ms-pulsars

- Precise timing with RXTE found periodic signals: burst oscillations
- 11 burst oscillation sources + 5 accreting pulsars (2 with burst oscillations): bimodal freq. distribution
- Why rotation? Large amplitudes during rise, high coherence (Q~4000), stable final frequency, but… drifts!





Propagation: deflagration burning



Burst oscillations indicate brightness asymmetries on the surface. Consider local ignition and subsequent deflagration

Rise time < 1s => front speed > 3×10^6 cm/s

heat propagation => front width

reaction speed

→ **speed of the flame** → **rise time of the burst**

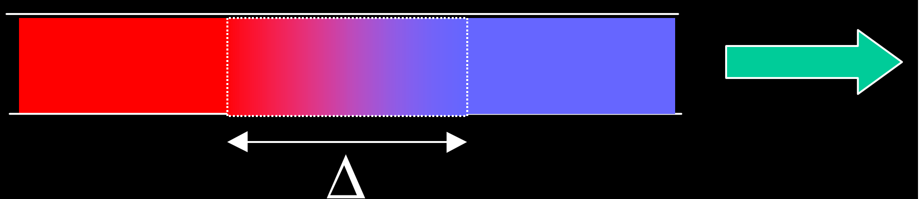
Estimates for mechanisms of heat transport (Fryxell & Woosley 1982)

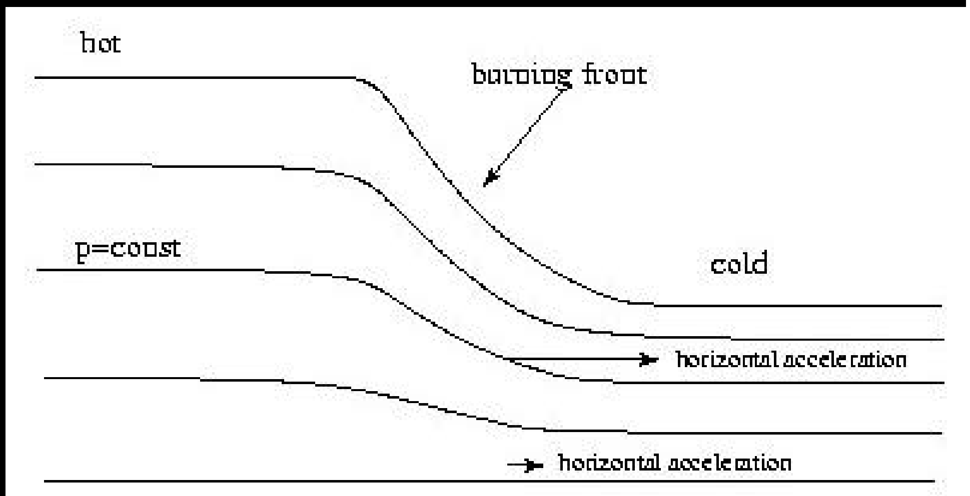
- Conduction: too slow (100 cm/s)
- Convection: convective speed 5×10^6 cm/s

1) Front width = scaleheight;	speed ~ 10^4 cm/s; too slow
2) Convective diffusion;	speed ~ 10^5 cm/s; too slow
3) "Wrinkled" front;	speed $\leq v_{conv}$ (upper limit)

- Consider missing physics: hydrostatic lift-up and rotation

Deflagration burning in hydrostatic atmosphere

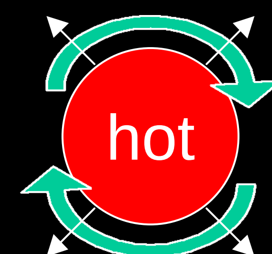




$h_{hot} \sim 10m$ $h_{cold} \sim 1m$

1. Nonuniform heating generates hydrostatic expansion
   and hydrodynamic flows (winds)

2. Winds transport entropy



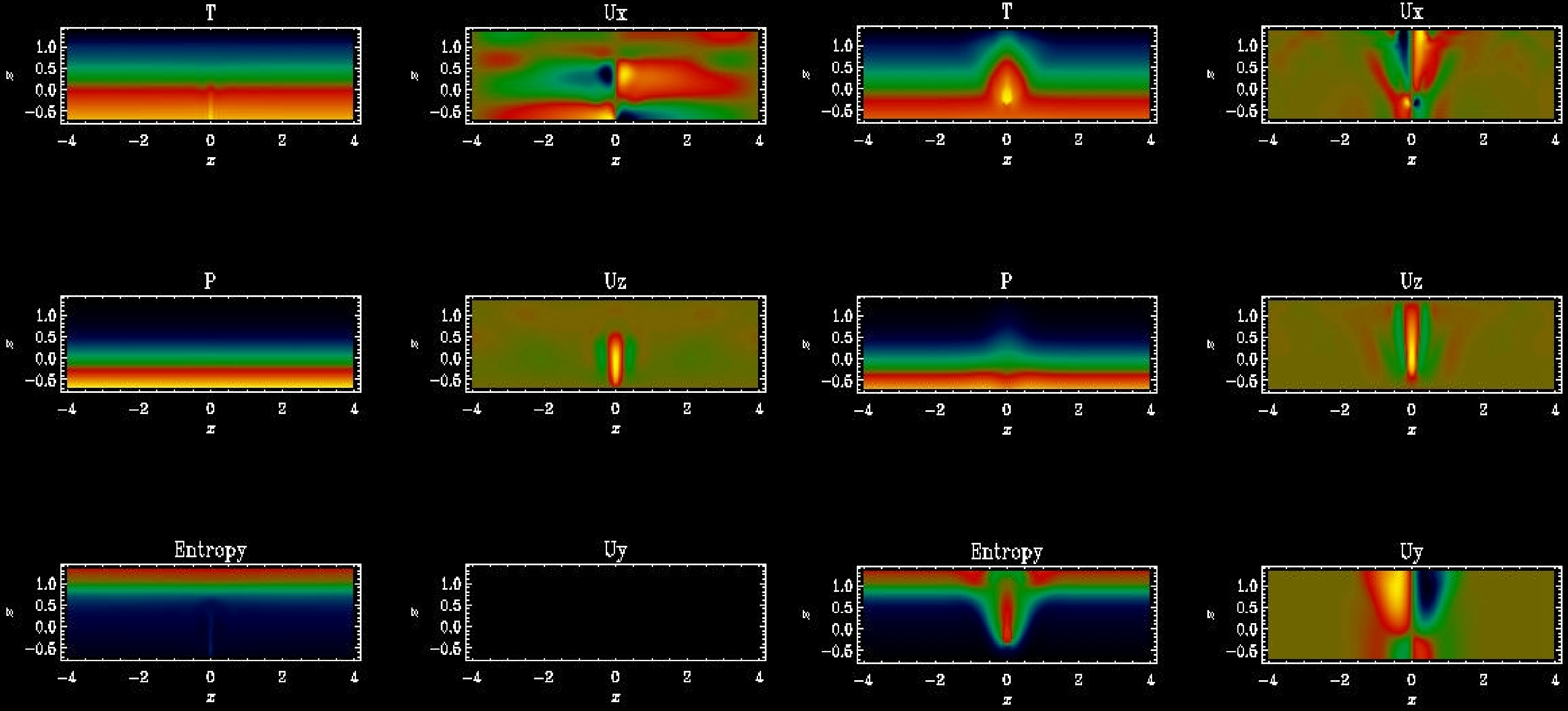
3. Winds are confined on the scale set by rotation → front width
   Is rotation important? $t_{nucl} \leq t_{rise} \sim 0.1 - 1\sec >> P_{rotation}$

Rotation is not only important to ignition, it is crucial!

Ignition in 2 dimensions: 2D hydro simulations

Local ignition is possible only if the temperature perturbation can be sustained on nuclear time scales

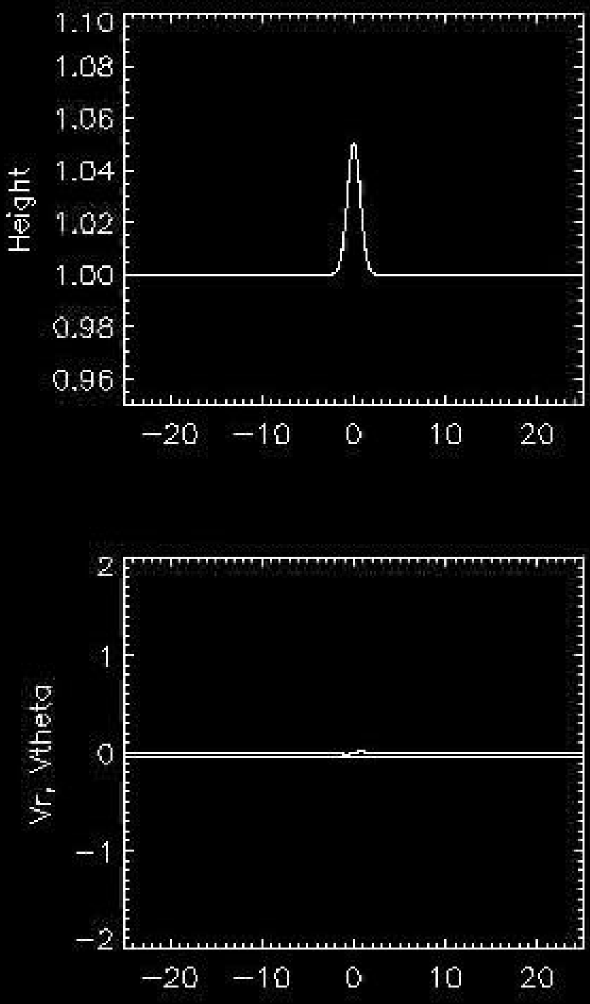
$\Omega = 0$ $\vec{\Omega}$ $\Omega \neq 0$



Rotation is able to confine the spread of temperature perturbations

Scale of the balance: Rossby radius of deformation

Scale where potential energy in perturbation = kinetic energy

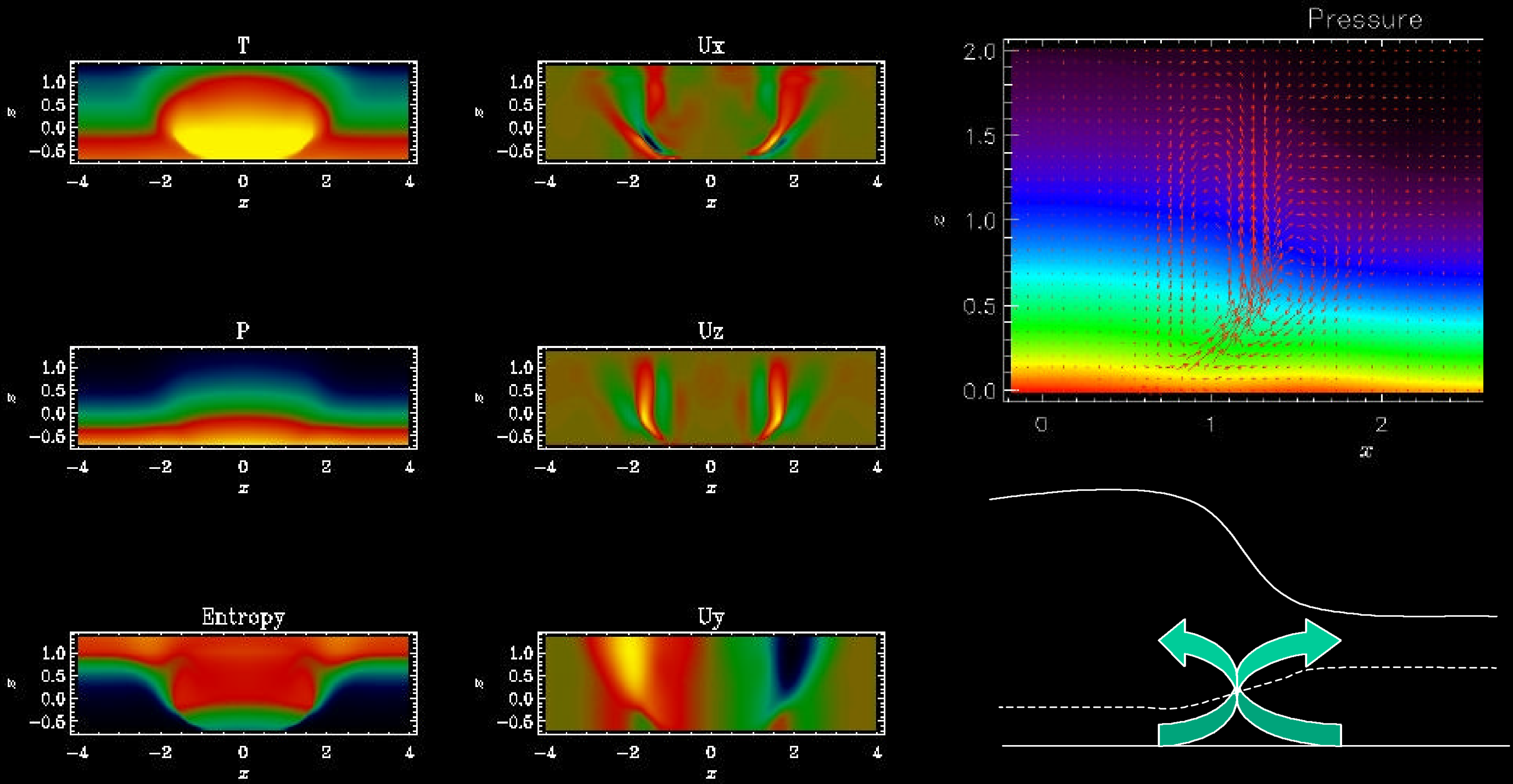


Rossby radius $a_R = \sqrt{gH} / 2\Omega$

a_R is a typical size of synoptic motions on Earth: ~1000 km, on NS ~ 1km

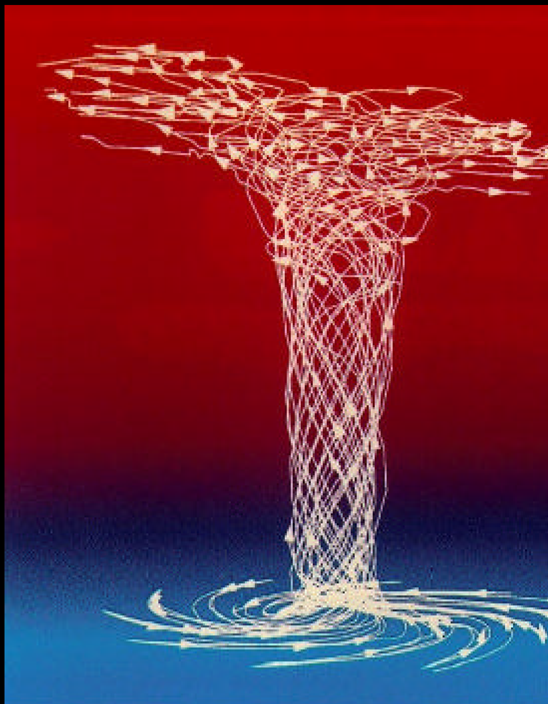
a_R/R ~ .1 for both Earth and NS. Ignition on NS is likely to start on Rossby scale.

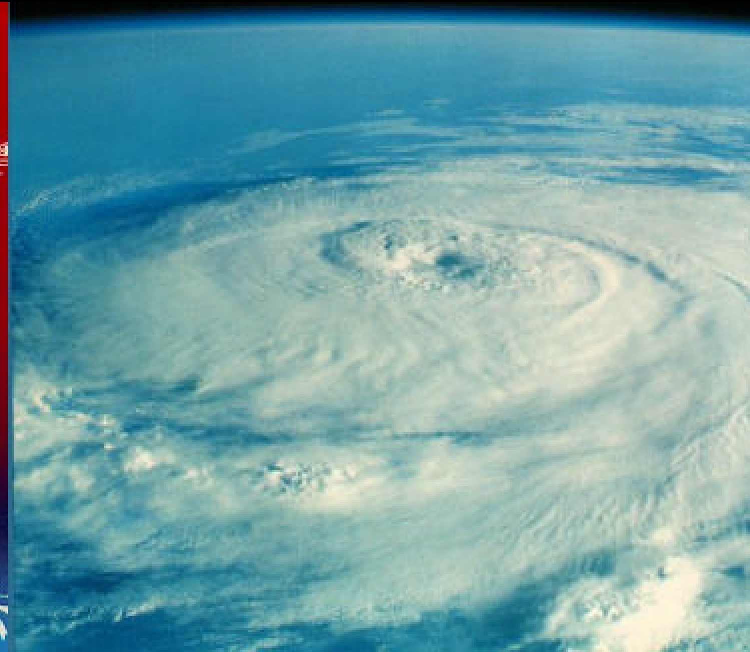
Burning front propagation

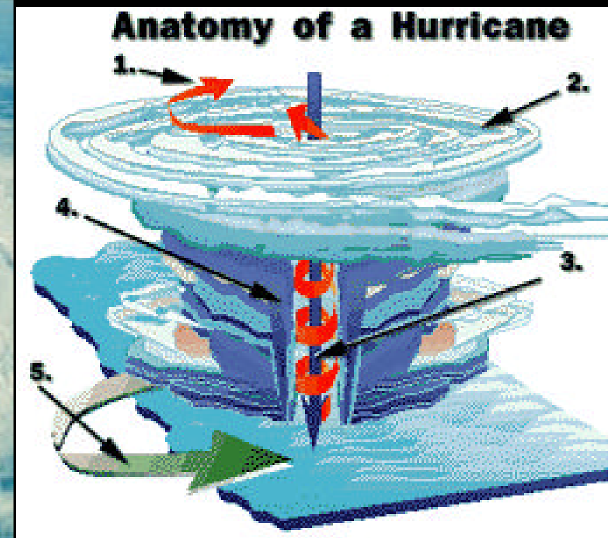


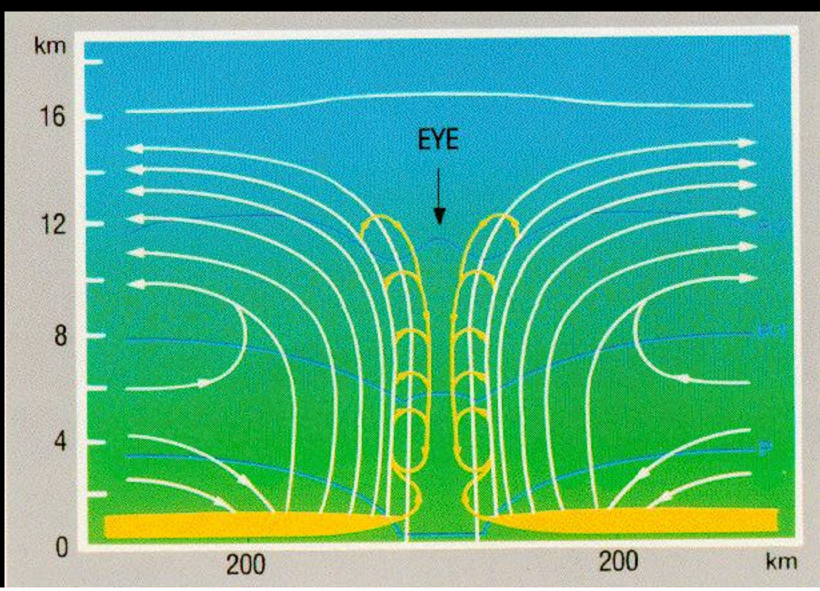
Front speed: front width / t_{nuc} = $a_R / t_{nuc} \approx 20 - 60\text{km/s}$

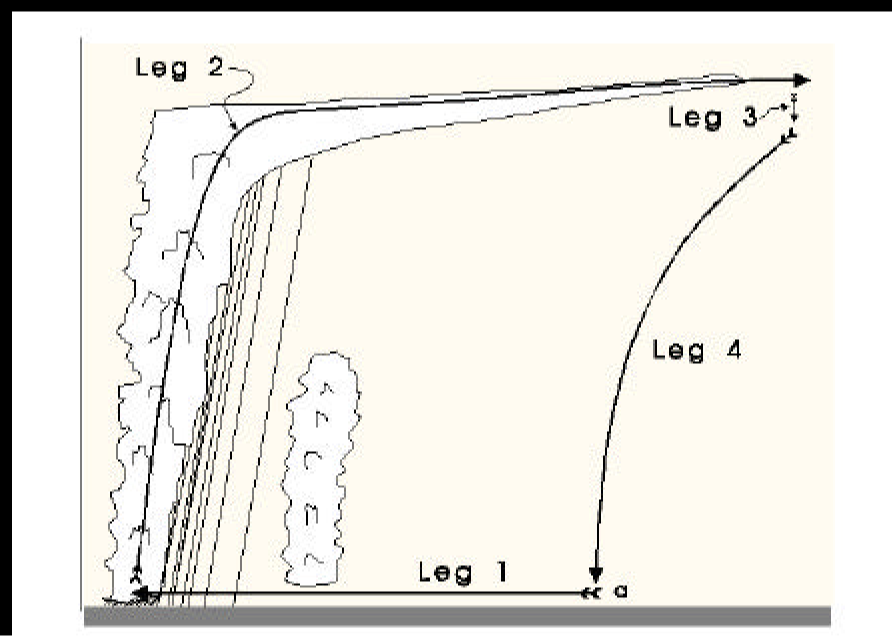
Analogy to hurricanes











Bursts dynamics

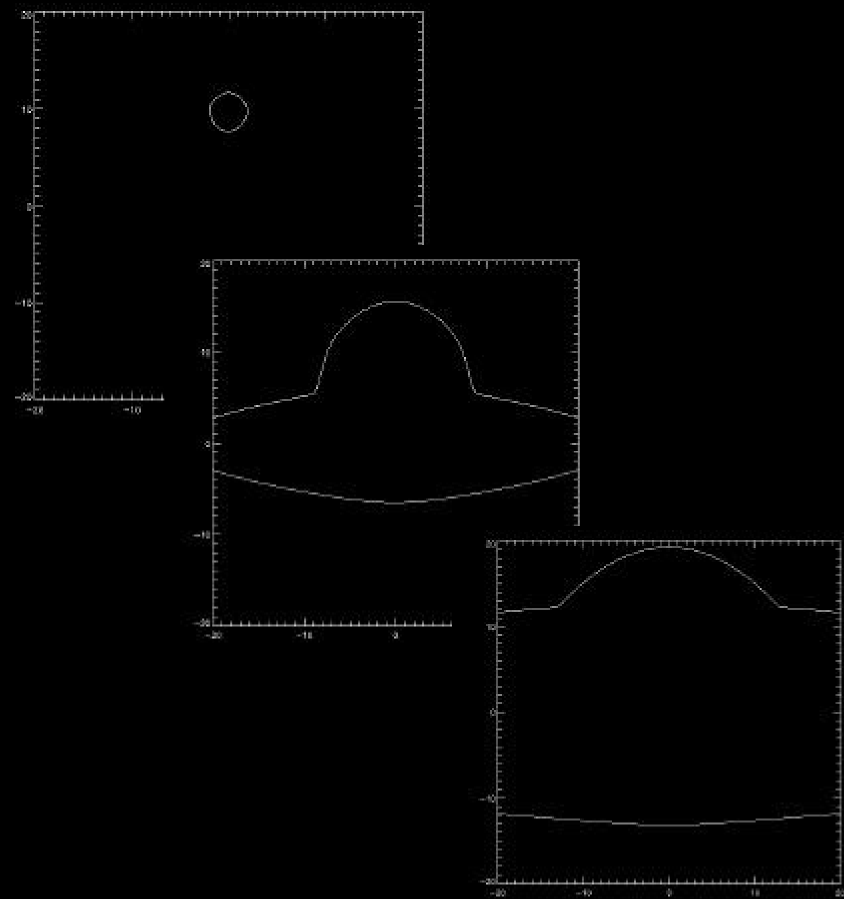
Walls of fire: equator to pole propagation

Burning creates spreading vortecies

Front speed depends on location on the star

Front spreads along equator faster than off equator: ignition of equatorial belt.

$$v_{flame} \sim \frac{\sqrt{g h_{hot}}}{(2\Omega \sin l \, t_{nucl})} \sim 2 - 6 \times 10^{6} \, \mathrm{cm/s}$$

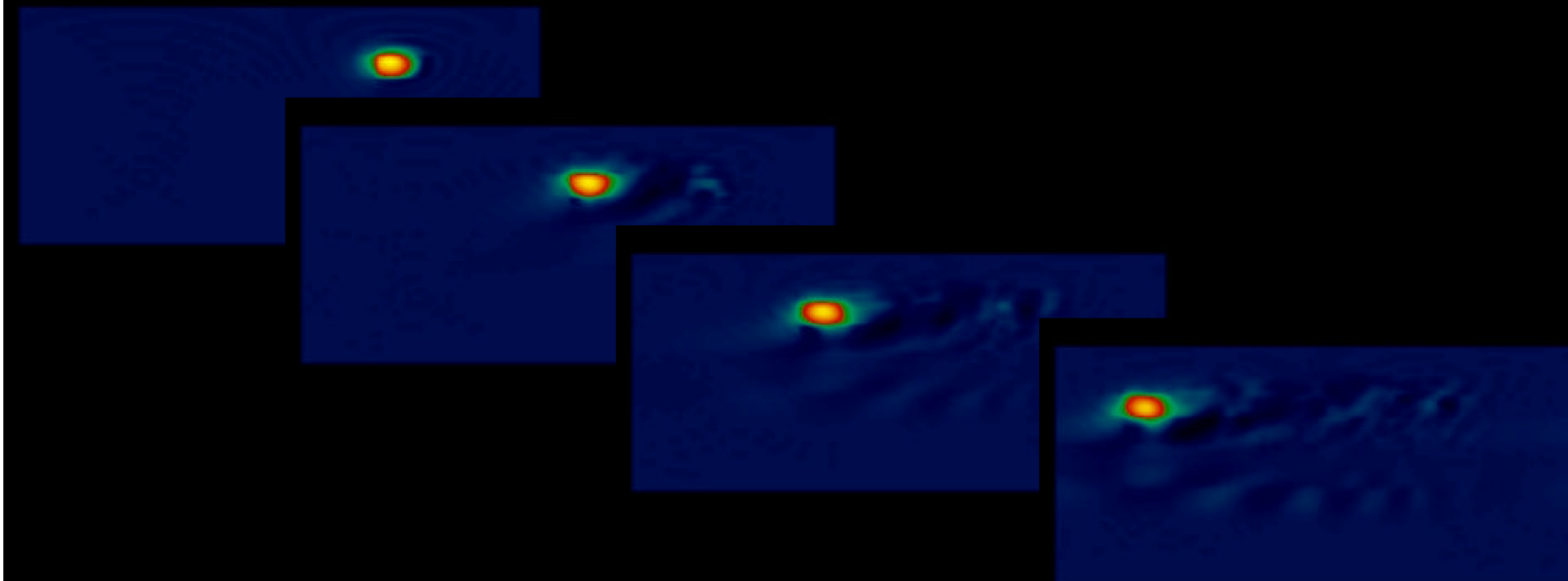


Ignition off equator

It is possible to ignite the star without creating large asymmetries

Evolution on a sphere

- Vortex evolution: two dimensional modeling on a sphere. Spherical shallow-water model. 500 turns of 300 Hz star.



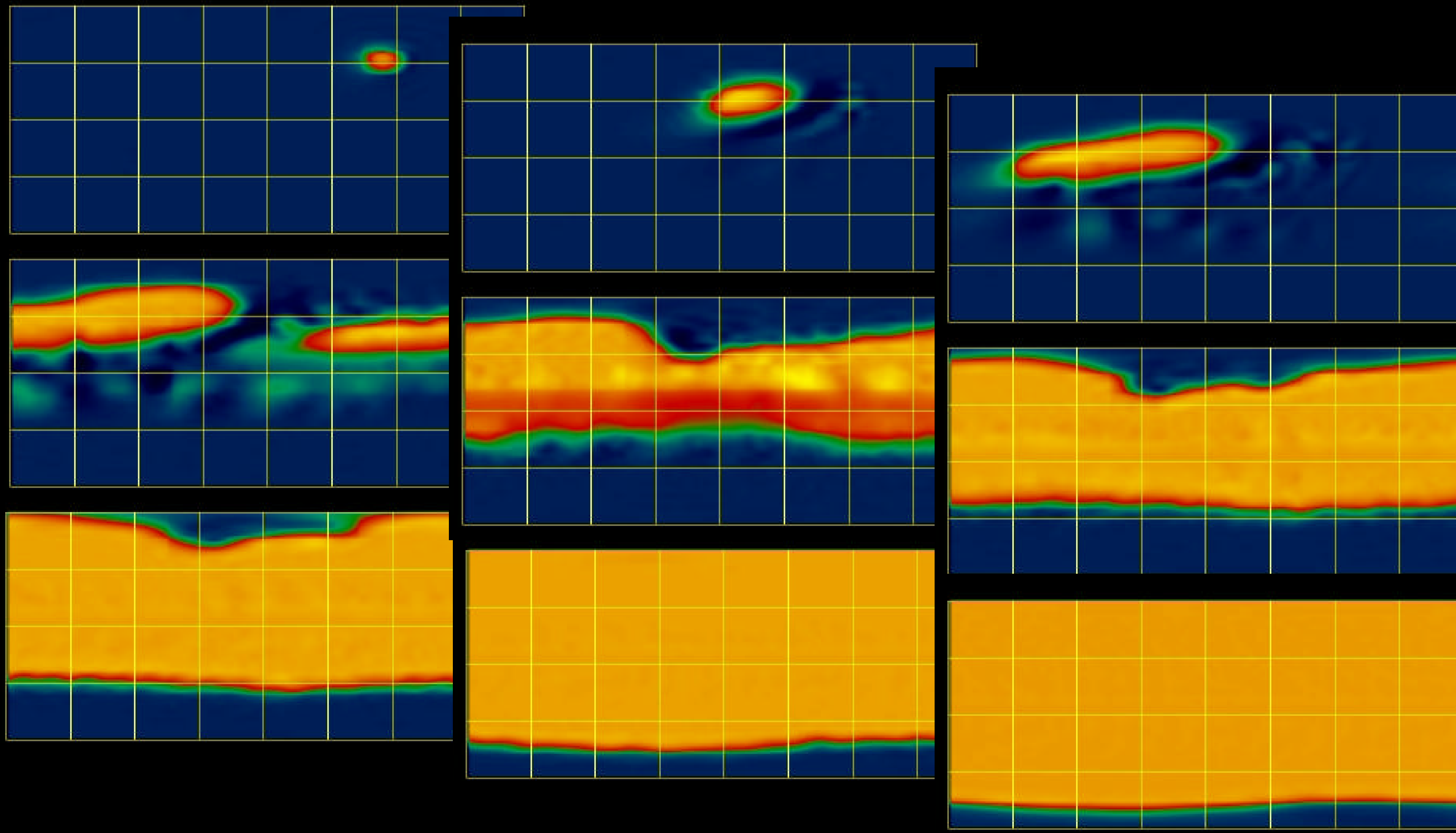
- New on a sphere: drift due to variation of Coriolis parameter over the surface -- beta-effect. $b = 2\Omega \cos J / R$ $\quad v_{b-drift} = r_{\max}^2 b$

$$\frac{\Delta\Omega}{\Omega} = \frac{gH}{R^2\Omega^2} = \frac{1}{e} = 0.01\left(\frac{300Hz}{n}\right)^2$$

- Rossby wave dispersion $\quad v_{phase} = b / k^2$

Ignition on a sphere

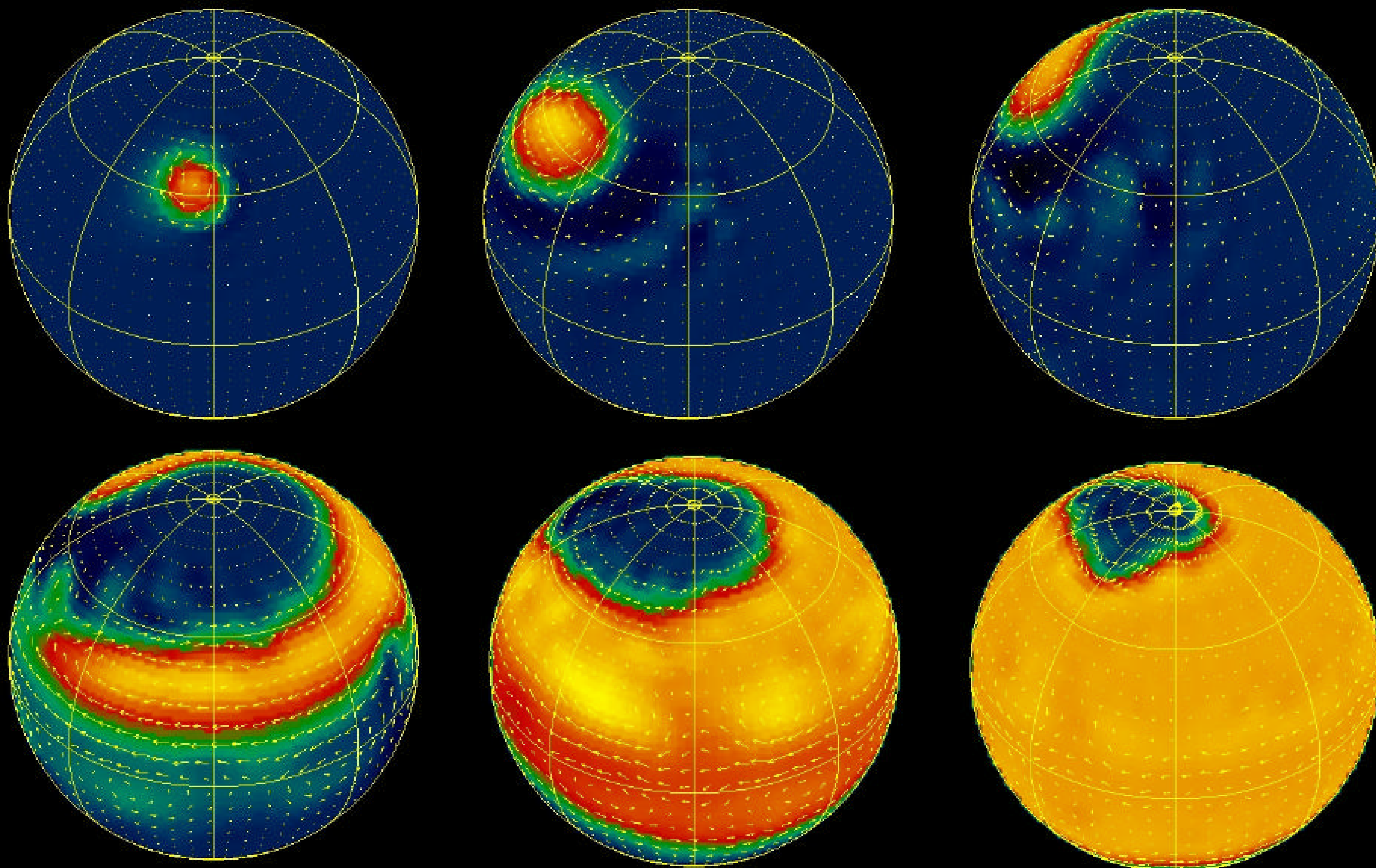
- 200 turns of 300 Hz star



- Spreading is preferentially along constant latitude lines. Faster spreading towards equator.

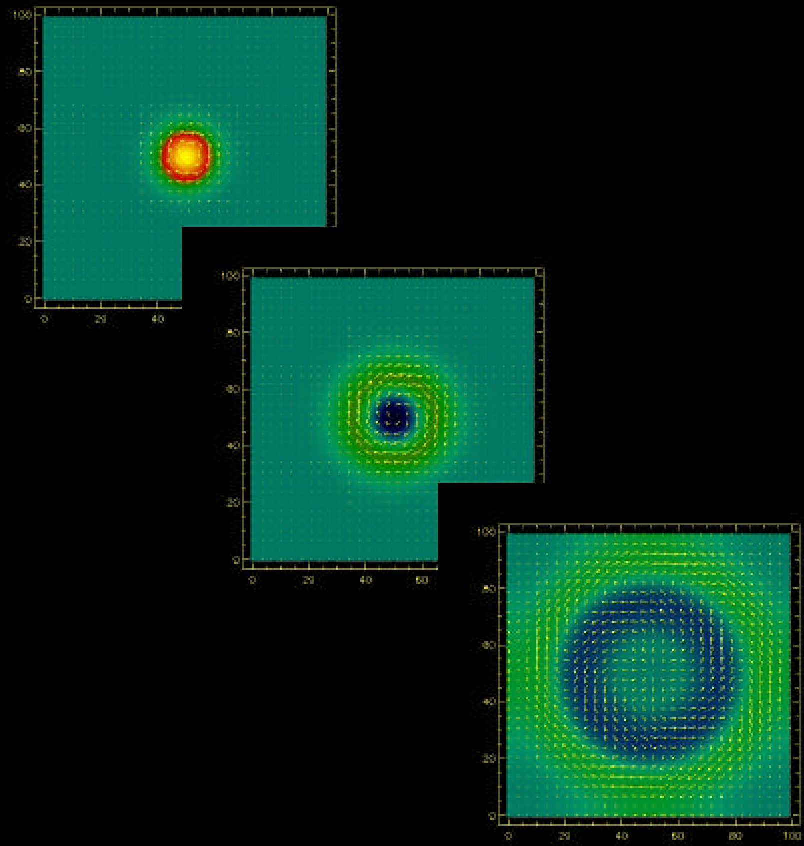
Ignition on a sphere

- 200 turns of 300 Hz star (spherical projection)



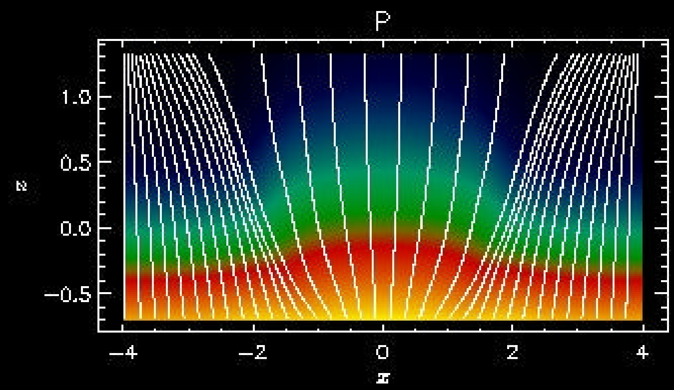
Magnetic field effects

- For some bursters (e.g., SAX 1808) field is strong enough to make persistent pulses. Also, vortecies can wind up even weak field.
- B field modifies internal vortex evolution



"Magnetostrophic adjustment"

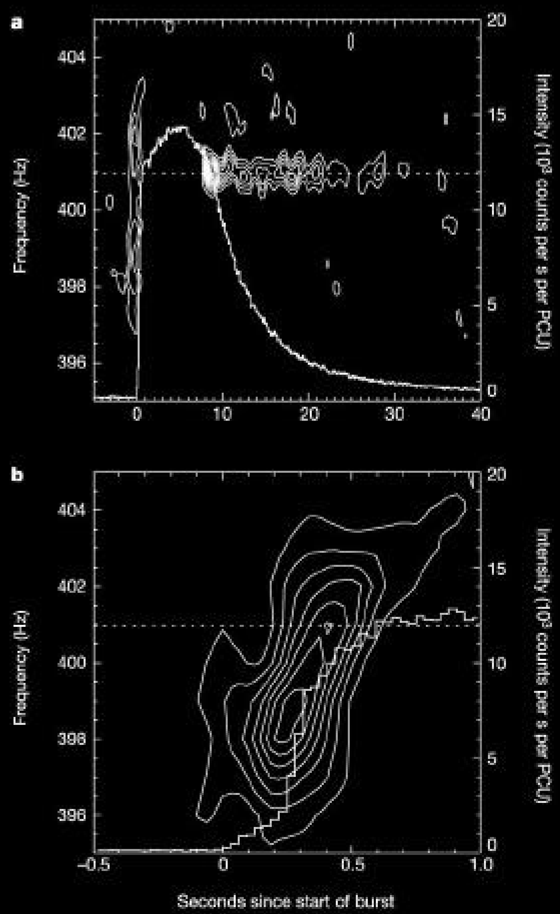
$$a_B = H\frac{v_g}{v_A} = 5km\left(\frac{10^8 G}{B}\right)\left(\frac{H}{10^2 cm}\right)$$



- Magnetic field stops geostrophic flow on the scale of magnetic adjustment radius.

Magnetic field effects: J1808

- B field modifies vortex motion, and can lead to dispersion and oscillation of coherent vortecies.
- Return to asymptotic frequency is faster for magnetic accretors. Damped harmonic oscillator model for frequency overshoots in J1808:



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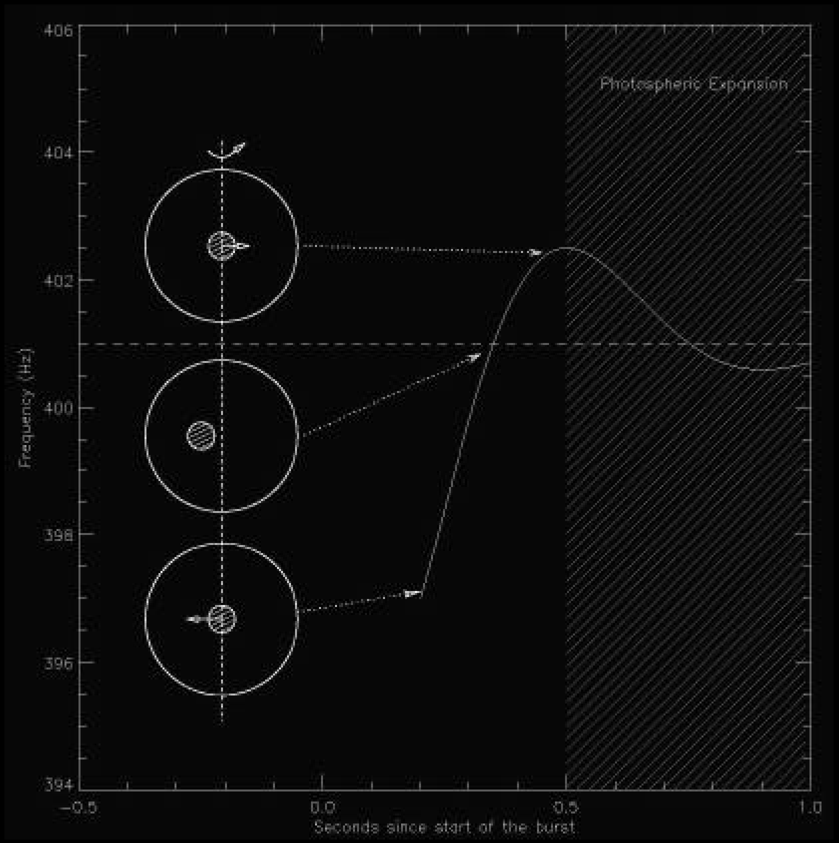
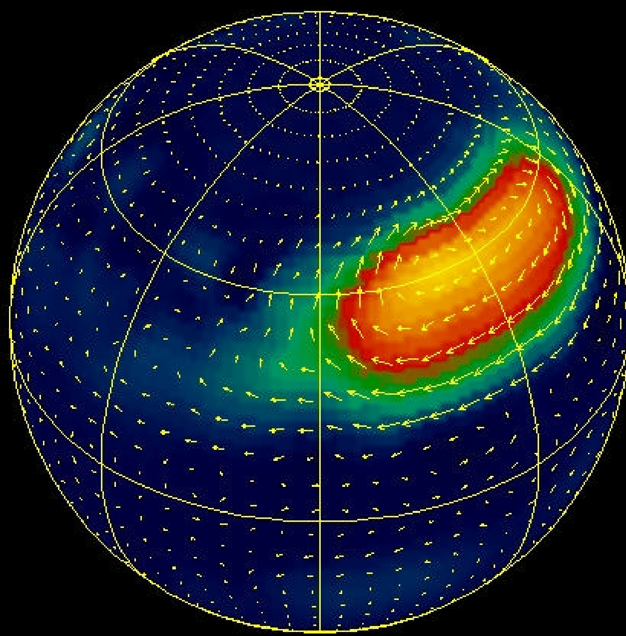


CONCLUSIONS

1. The model of burning front propagation based on geostrophic circulations is tested by full hydro numerical simulations.

2. Burning on sphere either starts on the equator or propagates to the equator and then in the form of “walls-of-fire” to the poles. Initial asymmetries are efficiently erased.
Vortex drift gives correct frequency change in the rise.

3. Oscillations in the tail of the bursts are likely due to equatorial modes that are excited when vortecies crash into the equator.



4. Dynamical effects of B-fields maybe important both to magnetic accretors and “nonmagnetic” bursters in order to bring the shell to corotation with star. Look for NS weather forecast on your local TV!