So, what is the weather like on Aquila X-1?

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El Niño, the Jet Stream and Type-I Bursts

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Contents

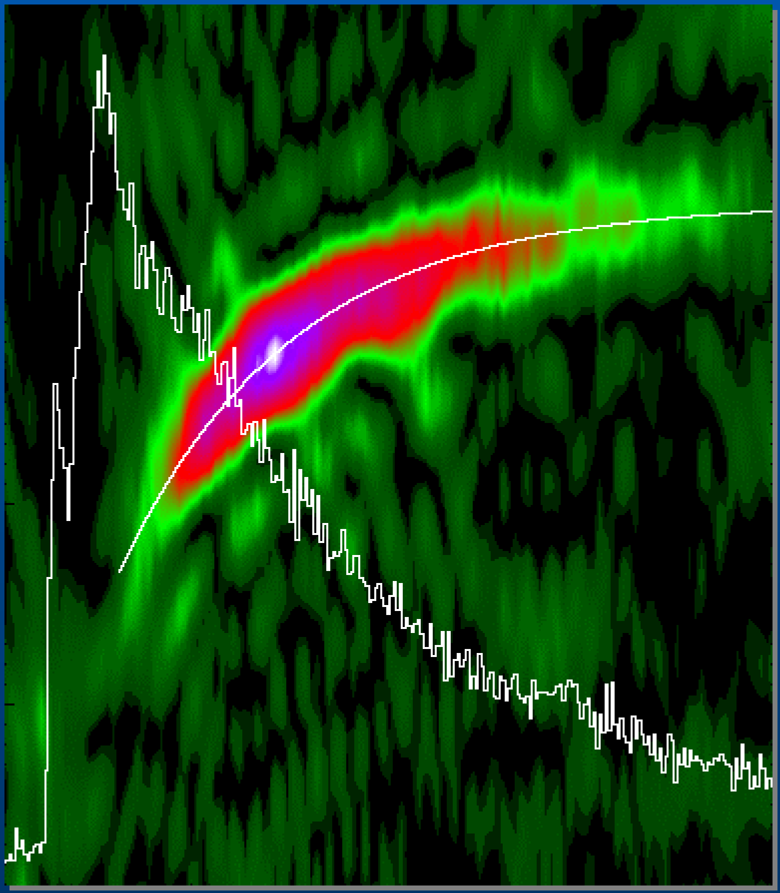
- What are Type-I bursts?
- Frequencies shifts and angular momentum
- What does GR have to say?
- What about the weather?
- What are ocean waves on a neutron star like?
  - Frequencies
  - Observables
- Prospects

What are Type-I X-ray Bursts?

- Nuclear burning on the surface of an accreting neutron star is generally unstable.
- The burst begins at a point and spreads over the surface in about one second.
- The flux during the burst varies periodically.

Frequency Drifts

- During the cooling portion of the burst, the observed frequency increases by about one Hertz.
- Angular Momentum Conservation (?)



FOR MORE INFO...

Strohmayer et al. '97, '98; Cumming & Bildsten '00

What's wrong with this picture?

- After a second, the whole surface is hot. Why is there a "hotspot"?
- Even in a Newtonian framework the atmosphere doesn't expands enough.
- GR increases the needed expansion.
- Should angular momentum be constant?

FOR MORE INFO...

Heyl '00; Abramowicz et al. '01; Cumming et al. '01 (0108099); van Straaten et al. '01; Wijnands et al. '01; Galloway et al. '01

Angular Momentum in Relativity

- In General Relativity, conservation laws are intimately connected with the symmetries of the spacetime.
- Killing vectors trace the symmetries.
- A hotspot traces a Killing trajectory,

$$u = N(\hat{t} + \Omega\hat{\phi}); L/m = u \cdot \hat{\phi}, E/m = u \cdot \hat{t}$$

- So we obtain

$$L/m = N(\hat{t} \cdot \phi + \Omega\hat{\phi} \cdot \phi); E/m = N(\hat{t} \cdot \hat{t} + \Omega\hat{\phi} \cdot \hat{t})$$

Enter General Relativity…

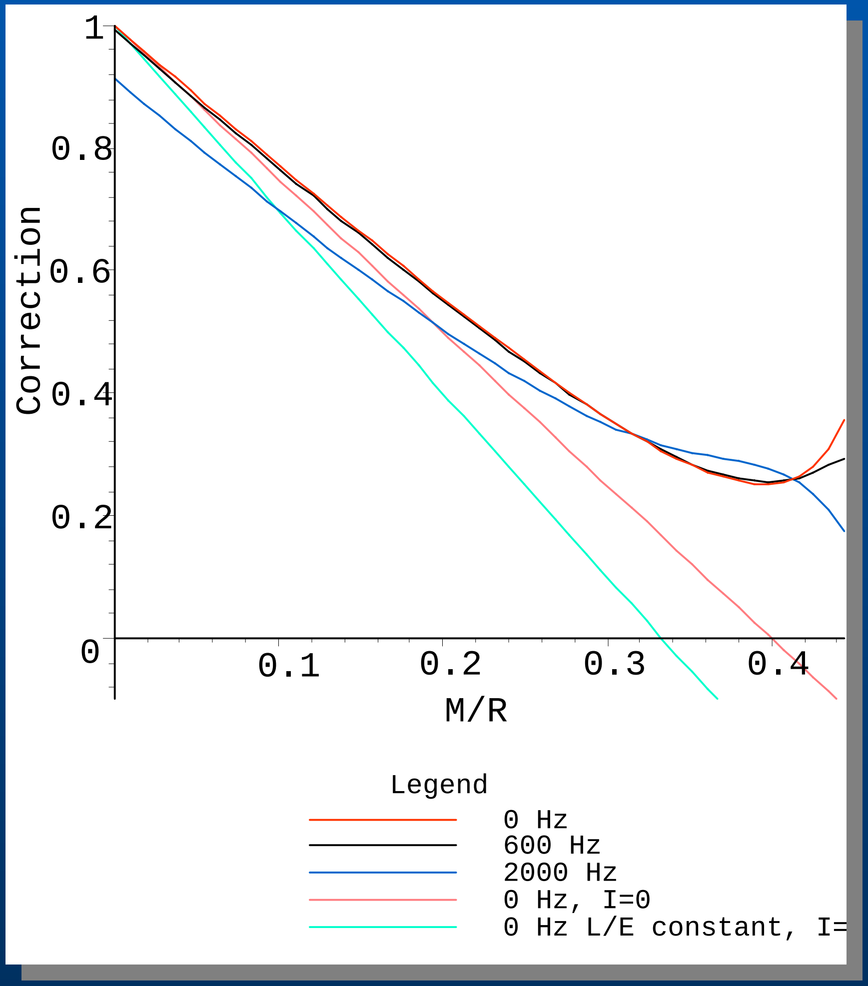
- How does spinning material “know” to slow down as it moves out?
- How does it know which way is out?
  - An interesting definition is what looks like out is out. Remember: gravity bends light.

< Horizon

$R<1.5R_s$ $R=1.5R_s$ $R>1.5R_s$

General Relativistic Corrections

- Three GR effects:
  - surface gravity
  - proper length
  - Killing vectors
- The first two reduce Δr for a given change in the atmosphere.
- The third affects the radius of gyration.



And Now for the Weather...

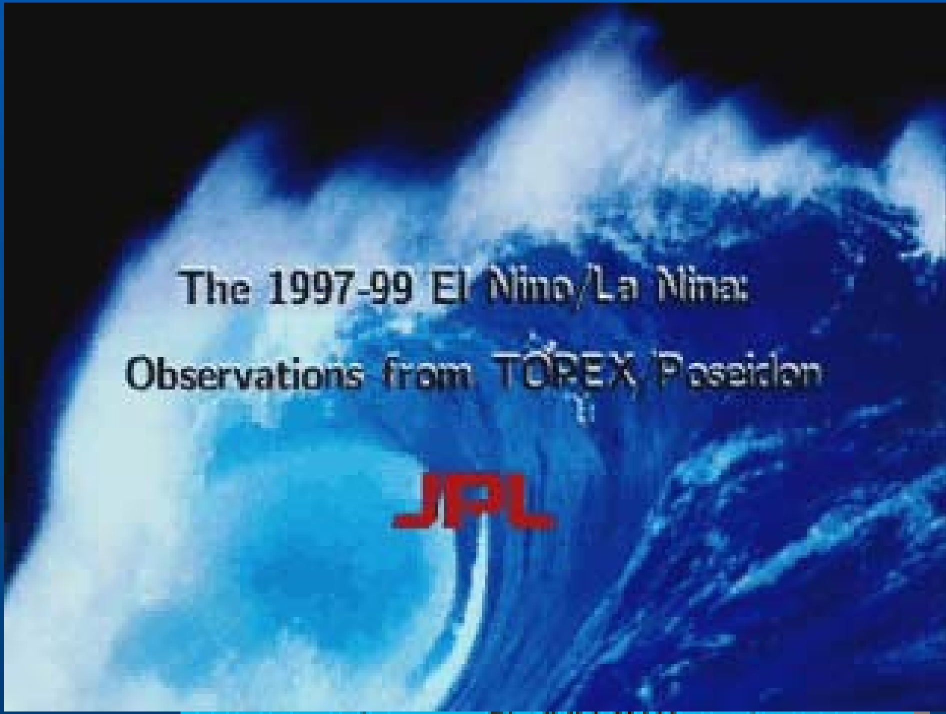
- The burning on the surface is complex.
  - Much slower than the sound speed
  - Yet significantly faster than deflagration
- It takes about a “year” (300 rotations) for the burning front to envelope the entire surface. Stellar rotation is surely important.

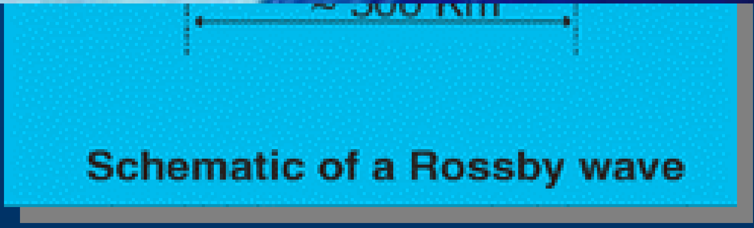
FOR MORE INFO...

Spitkovsky et al. ‘01 (cyclonic burning)

El Niño, La Niña and Jet Stream

- **Rossby waves and Kelvin waves travel slowly.**
- **Most other large-scale gravity modes are stuck near the equator.**




Schematic of a Rossby wave

FOR MORE INFO...

Southhampton Oceanography Centre; NASA/CNES TOPEX/Posidon; Weather.com

Neutron-Star Surface Waves

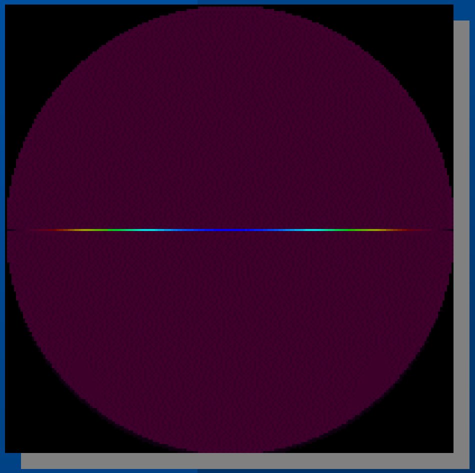
- Waves can be characterized by the value of $q = \Omega/\omega$.
- As the star rotates, the flux will vary at the angular frequency $|m\Omega - \omega|$.
- The frequency changes by 1 part in 300, so $q \approx 300$.

FOR MORE INFO...

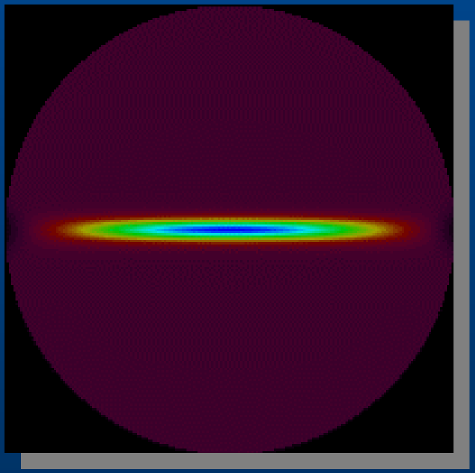
Bildsten, Ushomirsky, Cutler 1996; Longuet-Higgins 1968

Wave Gallery

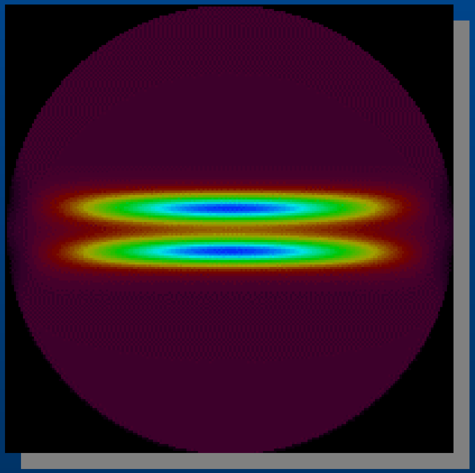
- **Frequencies decrease with the number of radial and latitudinal nodes!**
- **The surface waves with the highest frequencies are:**



Gravity wave

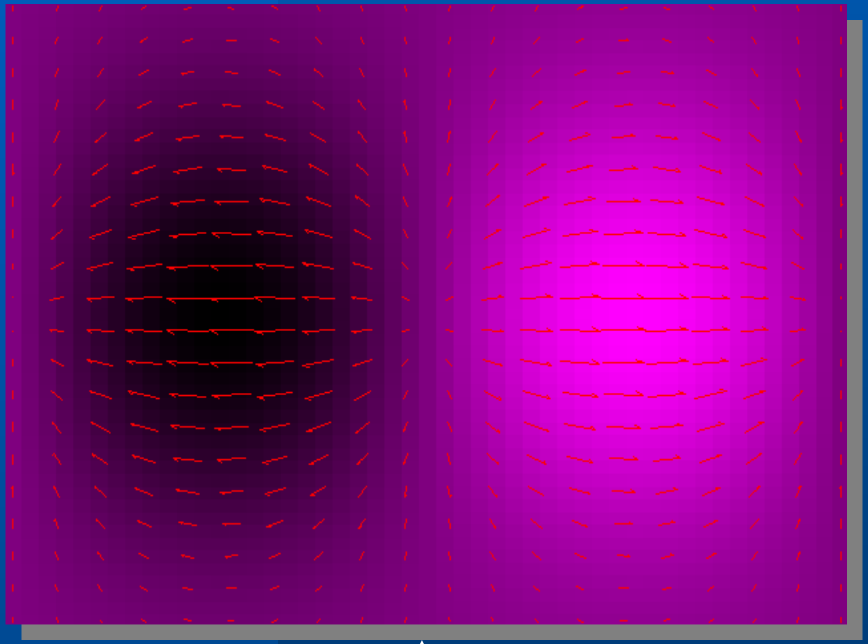


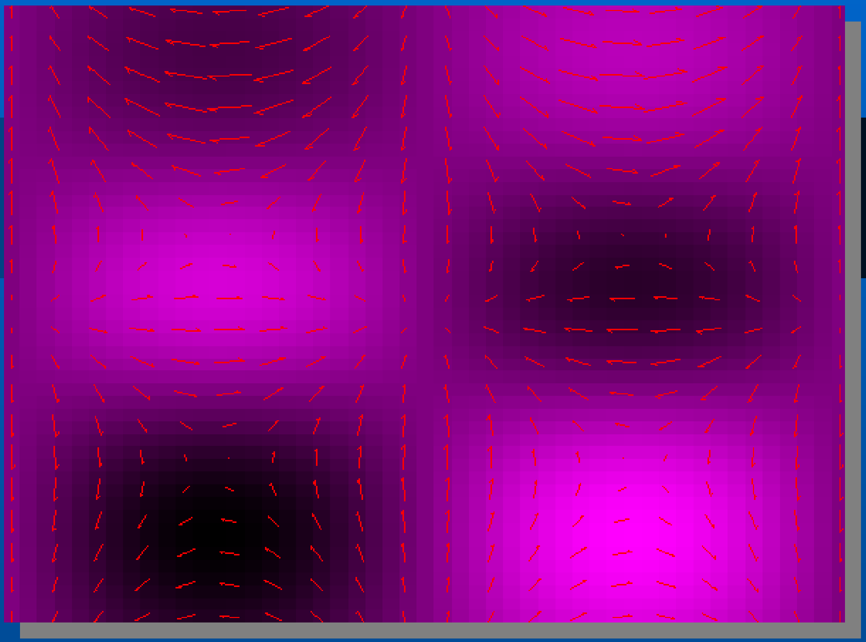
Kelvin wave

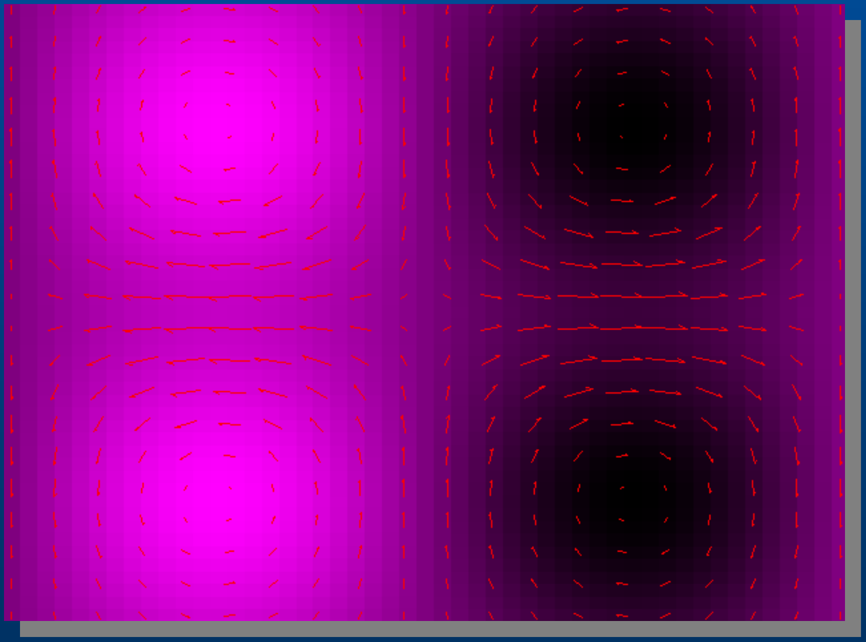


Rossby Wave

Wave Motions







Kelvin Wave ($\Delta r=0$)

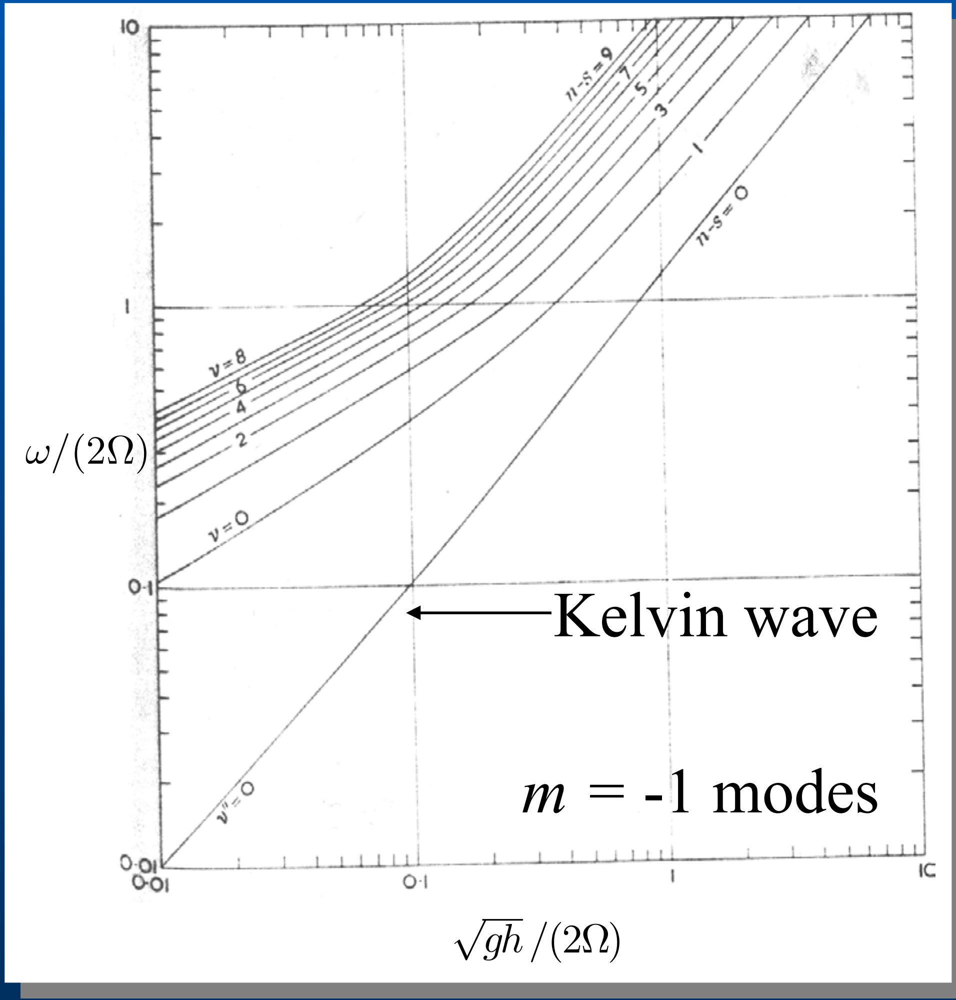
Rossby Wave

Wave Frequencies (Eastbound)

- The frequency depends strongly on the rate of rotation of the star.
- The frequency of one eastbound wave is constant.

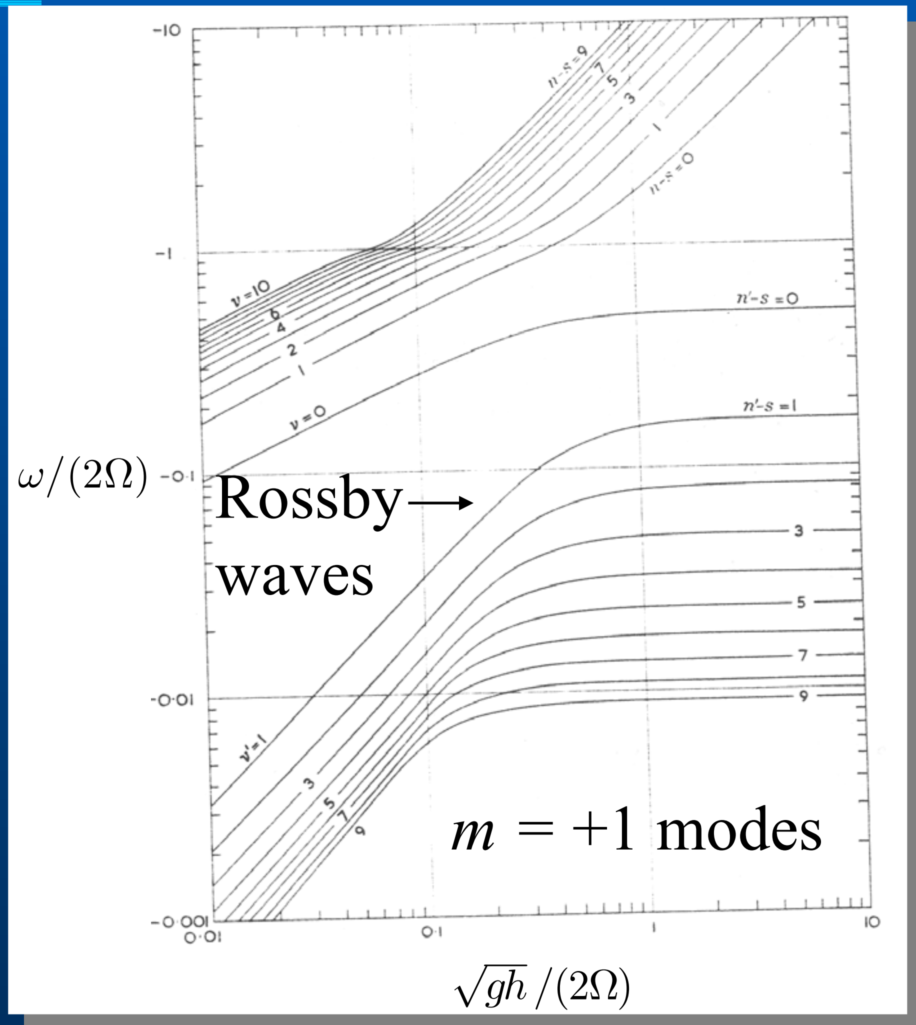
FOR MORE INFO...

Longuet-Higgins 1968



Wave Frequencies (Westbound)

- For a slowly spinning star, the Rossby waves oscillate at a fixed fraction of Ω.
- For a quickly spinning star, ω of the Rossby waves is constant.



Which waves would we see?

- **Modes that have a larger footprint on the star are more likely to be detected.**
- **The modes lie mostly in an equatorial band with**

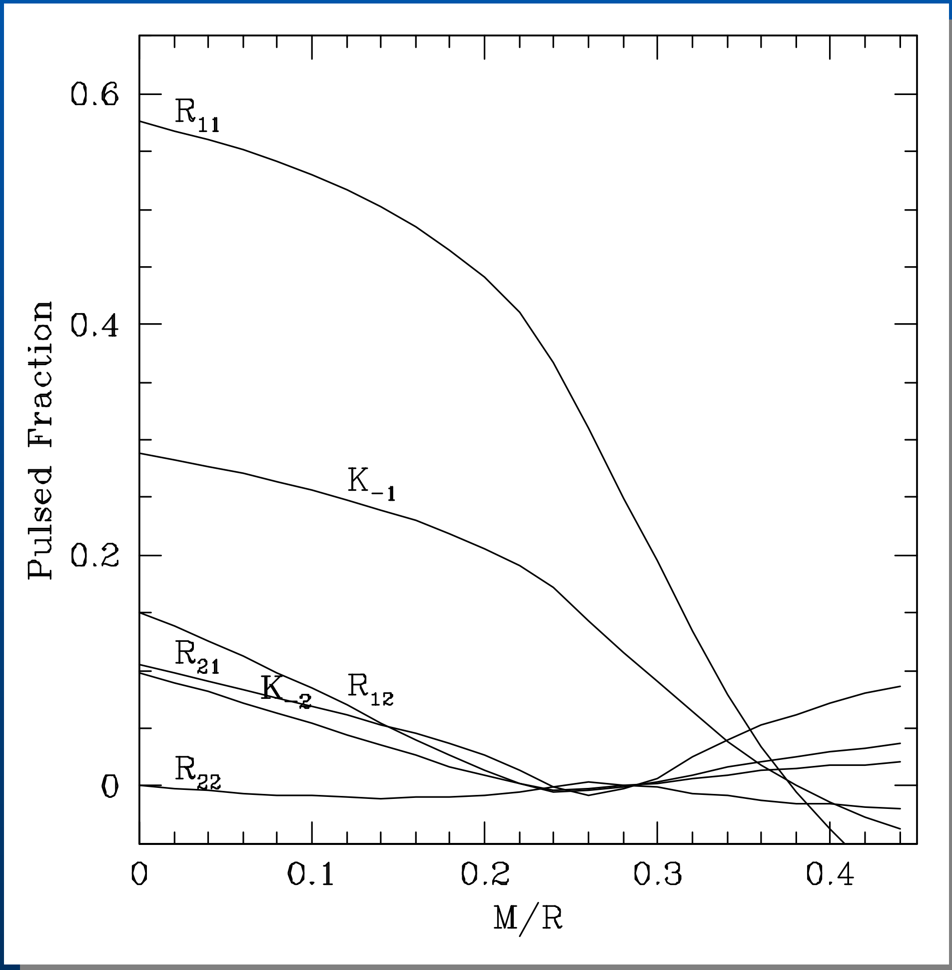
$$|\mu| < \begin{cases} q^{-1}(2+1/\nu)^{-1/2} & g-\text{mode} \\ |qm|^{-1/2} & \text{Kelvin mode} \\ |qm|^{-1/2}(2\nu^2+\nu)^{1/2} & r-\text{mode} \end{cases}$$

Pulsed Fraction

- For viewpoints near the equator (*l*=30°), the R_{11} wave is by far the most visible.
- Latitudinal, radial or extra longitudinal nodes reduce the footprint.

FOR MORE INFO...

Heyl '01 (0108450)



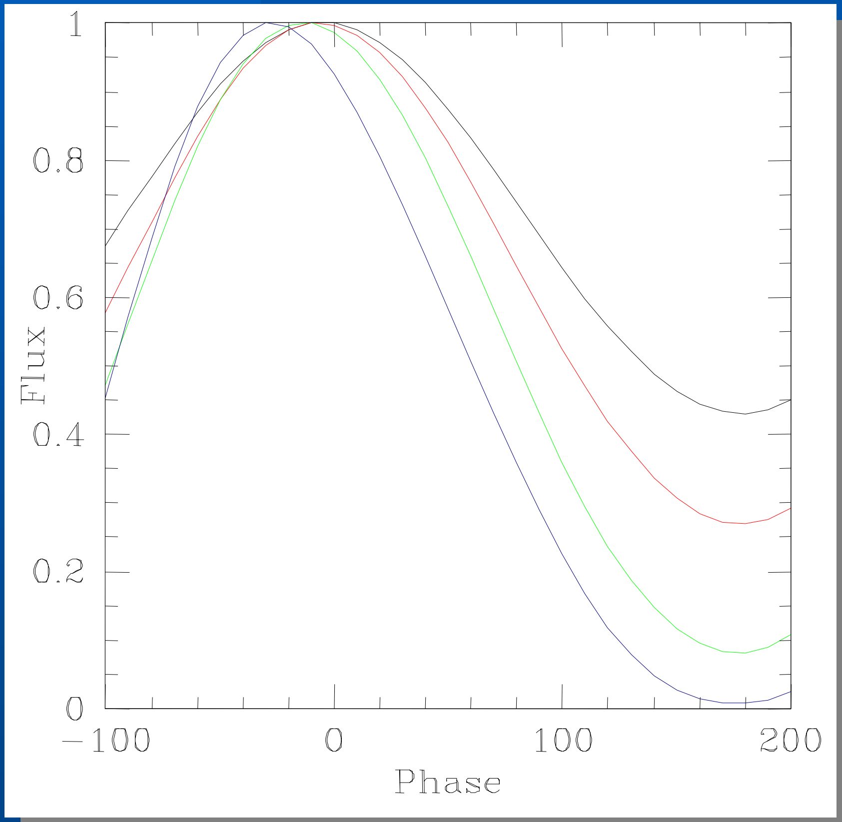
Why is there a frequency shift?

- **The frequency of the wave depends on the properties of the ocean layers through which it propagates.**

$$2.4\mathrm{Hz}\ \ m T_8^{1/2} R_6^{-1} A_{56}^{-1/2} (1 + 0.47 n^2)^{-1/2} (2\nu + 1)^{-1}$$

- **As the ocean cools or *A* increases, the frequency decreases.**
- **We observe an oscillation at $\Omega - \omega$ (*r*-mode) or $\Omega + \omega$ (Kelvin wave).**

How do the oscillations appear?



- The oscillations are more pronounced at higher energy (assuming blackbody emission).
- The pulse is earlier in phase for higher energy photons (Doppler shift).
- The pulse shape is set by the wave pattern and the atmosphere.

Contrast with the Standard Model

- It works. For iron, one would expect ω to change by about 1.4 Hz enough to account for the observations.
- Stars with different spin frequencies would exhibit the same absolute change in oscillation frequency.
- The final frequency of the oscillation is not necessarily constant from burst to burst.

Prospects

- Potentially other waves might be excited and observed:
  - Kelvin waves ($\Delta f \sim 5$ Hz)
  - Higher-order Rossby waves ($n > 0$)
  - Each wave would appear in the dynamic power spectrum.
- Also waves with $|m| > 1$ could be excited and seen at $|2\Omega - \omega|$.
- A connection with cyclonic burning?