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

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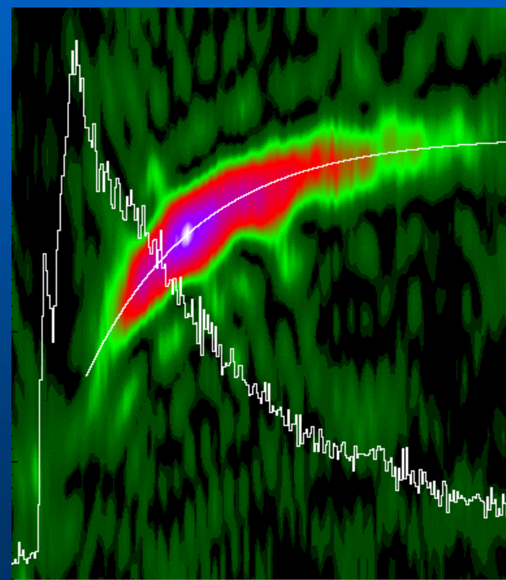
What are Type-I X-ray Bursts?

- 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)

And Now for the Weather...

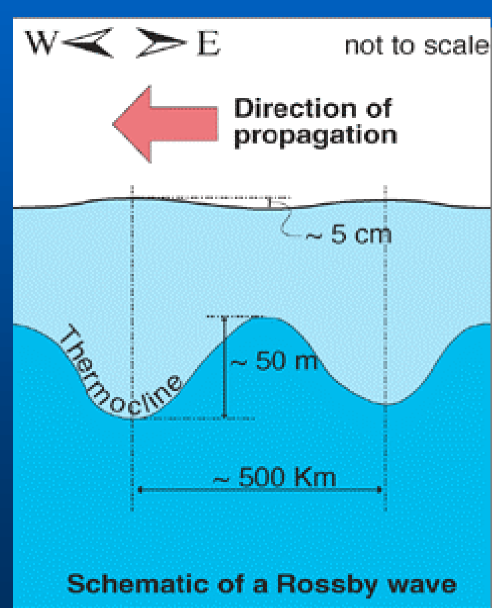
- The burning on the surface is complex.
  - Much slower than the sound speed
  - Yet significantly faster than deflagration
- It takes about a "year" (300 rotations) for the burning front to envelope the entire surface. Stellar rotation is surely important.

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.



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

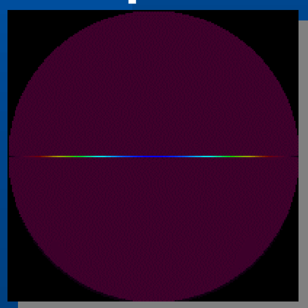
Which waves would we see?

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

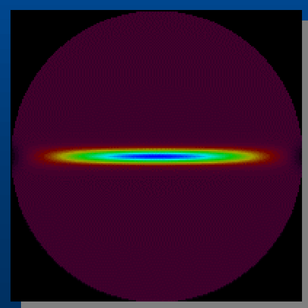
$$|\mu| < \begin{cases} q^{-1}(2 + 1/\nu)^{-1/2} & g-\text{mode} \\ |qm|^{-1/2} & \text{Kelvin mode} \\ |qm|^{-1/2}(2\nu^2 + \nu)^{-1/2} & r-\text{mode} \end{cases}$$

Wave Gallery

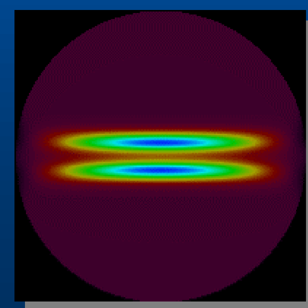
- Frequencies decrease with the number of radial and latitudinal nodes!
- The surface waves with the highest frequencies are:



Gravity wave



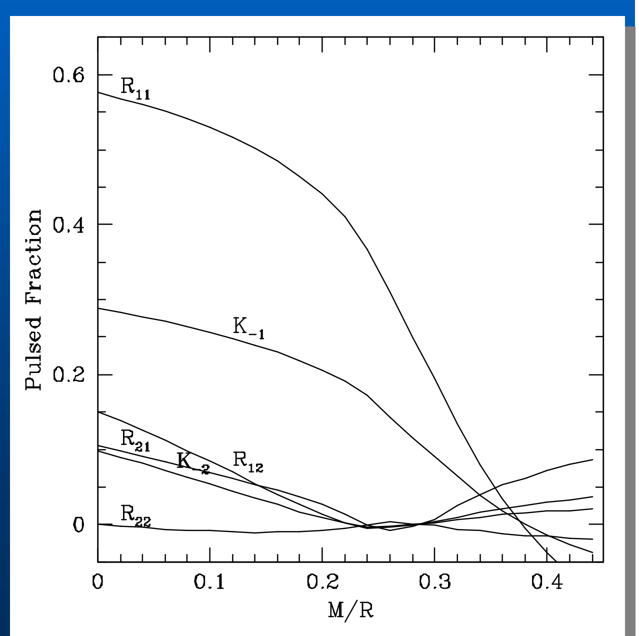
Kelvin wave



Rossby Wave

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).**

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.**
- **Other modes may be excited which exhibit different frequency shifts; *e.g.* the Kelvin mode shifts by 5 Hz.**