Using KEPLER to constrain nuclear reactions

Sarbani Basu
Yale University
**Kepler does more than search for planets. Kepler also has a programme to study stars through stellar pulsations.**
Solar-like oscillators have substantial outer convection zones that randomly excite pulsations.
Huber et al. 2011
Describing the modes

Eigenfunction oscillates as function of $r$ when

$$\omega^2 > S_l^2, N^2 \quad \text{p modes} \quad S_l^2 = \frac{l(l + 1)c^2}{r^2}$$

$$\omega^2 < S_l^2, N^2 \quad \text{g modes} \quad N^2 = g \left( \frac{1}{\Gamma_1} \frac{d \ln p}{dr} - \frac{d \ln \rho}{dr} \right) \approx \frac{g^2 \rho}{p} (\nabla_{ad} - \nabla + \nabla_{\mu})$$

$$\frac{d^2 \xi_r}{dr^2} \approx -\frac{\omega^2}{c^2} \left( \frac{S_l^2}{\omega^2} - 1 \right) \left( \frac{N^2}{\omega^2} - 1 \right) \xi_r$$

Model of present Sun
P-modes: Equidistant in frequency

\[ v_{nl} \approx \Delta v \left( n + \frac{\ell}{2} + \alpha \right) + \epsilon_{nl}, \quad \text{where} \]
\[ \Delta v = \left[ 2 \int_0^R \frac{dr}{c} \right]^{-1} \]

G-modes: Equidistant in period

\[ P_{n+1,1} = P_{n,1} + \frac{P_0}{\sqrt{2}}, \quad \text{where} \]
\[ P_0 = 2 \left( \int_0^{r_c} \frac{N}{r} \right)^{1} \]
What does Kepler observe?

The observed low degree modes are sensitive to stellar cores.
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How can Kepler data say anything about Nuclear Reactions Rates?

By examining the properties of stellar cores.
Example: The size of the convective core

Complication? Overshoot!

\[ ^{14}N(p, \gamma)^{15}O \]

Fig. courtesy Joel D. Tanner
Not just higher mass stars

Fig. courtesy Joel D. Tanner
Low mass stars, change in p-p rate

50% lower

50% higher
Low mass stars: CNO rates

50% higher
CNO rates: higher mass stars

All three models have the same M and R. CNO rates higher in both test models
Some seismic diagnostics already exist

\[ D_{\ell \ell+2}(n) = \frac{\delta_{\ell \ell+2}(n)}{4 \ell + 6} = \frac{\nu(n, \ell) - \nu(n-1, \ell+2)}{4 \ell + 6} \]

\[ \eta(n_1, n_2) = \left( \frac{\Delta \Omega}{\Delta} \right)^2 \left( \frac{\Delta}{\Delta} \right)^2 \left( D_{13}(n) - D_{02}(n) \right)^2 \]

Mazumdar et al. 2006
Helium burning stars.

Bedding et al.
Concluding thoughts

- It looks possible that seismic signatures from stellar cores can be used to constrain stellar nuclear reaction rates.

- We need to do more work to develop diagnostics.

- Unlike solar constraints, the constraints can be obtained only in a statistical manner.