Collective **velocity broadening** from **gravity waves** as a plausible mechanism for **macroturbulence** in **massive stars**

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Take home message:

Massive stars excite gravity waves which cause angular momentum transport and the tangential velocity field needed for macroturbulence

Introduction

Understanding the interior physics of massive stars is an important goal for **asteroseismology** as such stars are prevalent in stellar and galactic evolution theory. Without observational constraints of internal **rotation, mixing and angular momentum mechanisms** in massive stars, which can strongly influence stellar evolution, the accuracy of stellar models is limited [1].

The TESS mission is currently observing hundreds of massive stars and provides an excellent opportunity to study physics that is not currently included in evolutionary models, specifically angular momentum transport from **Internal Gravity Waves** (IGWs).

Models of IGWs

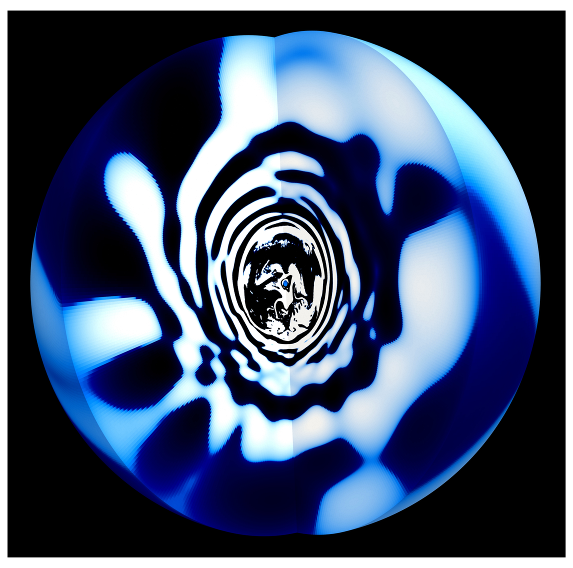

Figure 1: 3D snapshot of temperature fluctuations caused by IGWs excited by core convection [2].

Numerical simulations of stellar interiors (e.g. Fig. 1) show that IGWs excited by core convection are very effective at transporting angular momentum [2].

An ensemble of IGWs spans a wide range of spatial scales, produces **stochastic low-frequency variability** and a large-scale tangential velocity field at the stellar surface [3], as shown in Fig. 2.

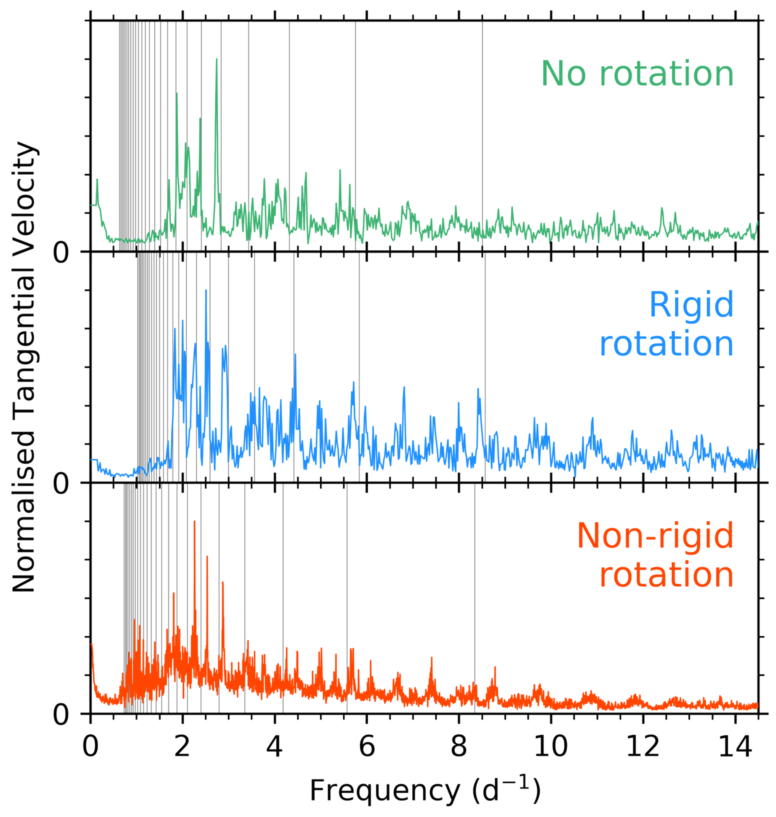

Figure 2: Tangential velocity spectrum caused by IGWs in numerical simulations for three interior rotation scenarios [3].

Photometry of IGWs

A large sample of massive stars observed by the CoRoT, Kepler, K2 and TESS missions, reveal that the photospheric signatures of **IGWs are ubiquitous** in time-series photometry [4,5].

The amplitude spectra of these time series are fit using:

$$\alpha(\nu) = \frac{\alpha_0}{1 + (\frac{\nu}{\nu_c})^{\gamma}} + C \quad (1)$$

where α_0 is the amplitude, ν_c is the characteristic frequency and γ is the logarithmic amplitude gradient and C is a white noise term. An example of a fitted amplitude spectrum for the O4V star HD46223 is shown in Fig. 3.

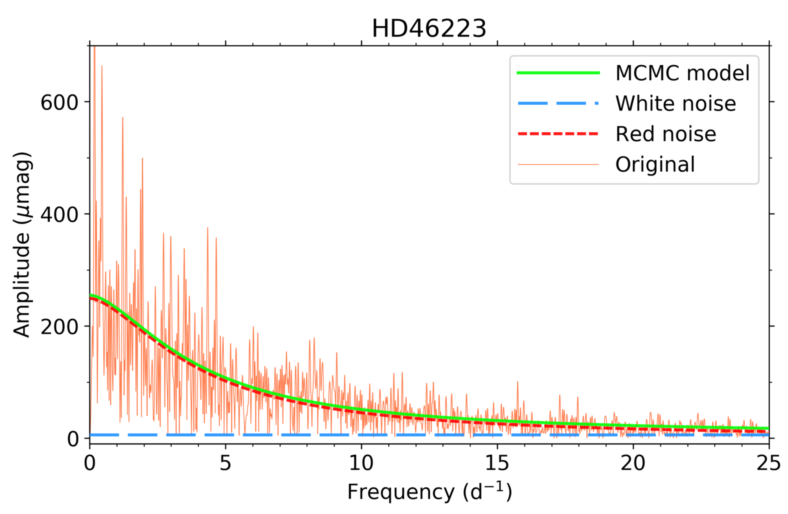

Figure 3: TESS amplitude spectrum of HD46223 showing stochastic low-frequency variability from IGWs.

IGWs in TESS data of massive stars

We studied 70 massive stars observed by the TESS mission [6] that also have **high-resolution spectroscopic parameters** in the IACOB data base [7]. We fit the TESS amplitude spectra using Eq. 1, and in Fig. 4 plot each star's location in the HR diagram.

The observed amplitude spectra agree with those of IGWs excited by core convection in numerical simulations [2]. We find a clear relationship between a **massive star's location in the HR diagram** and the amplitude and frequency range of its stochastic low-frequency variability in photometry caused by IGWs [5].

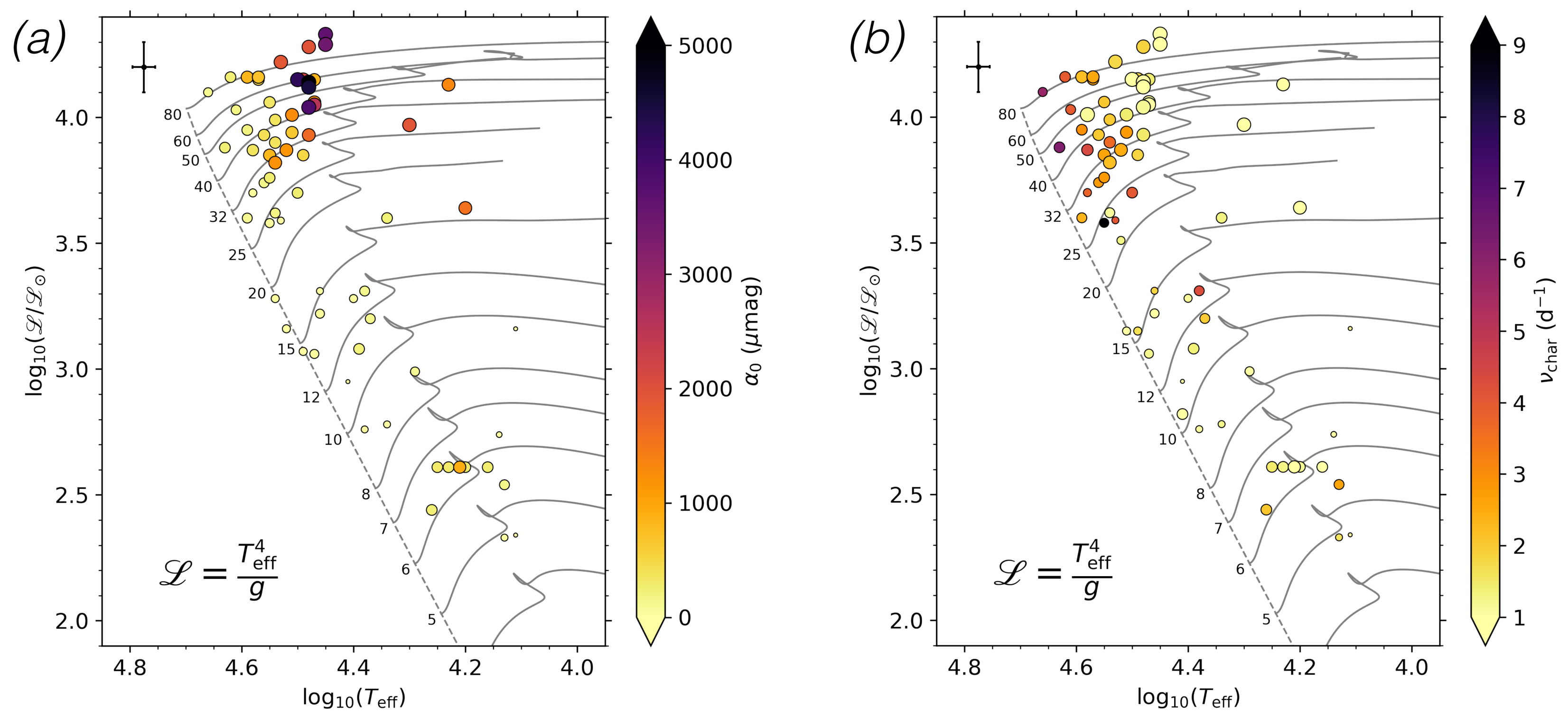

Figure 4: Spectroscopic HR diagram for massive stars showing IGWs: more luminous stars have larger IGW amplitudes (a) and lower IGW frequencies (b).

Correlations with Macroturbulence

We also find a clear correlation between the **amplitude of IGWs** in photometry and the amount of **macroturbulence** in spectroscopy, as shown in Fig. 5. Therefore the predominantly horizontal velocities of IGWs, just like coherent gravity modes in late-B stars [8], are a plausible mechanism to explain macroturbulence in massive stars [5].

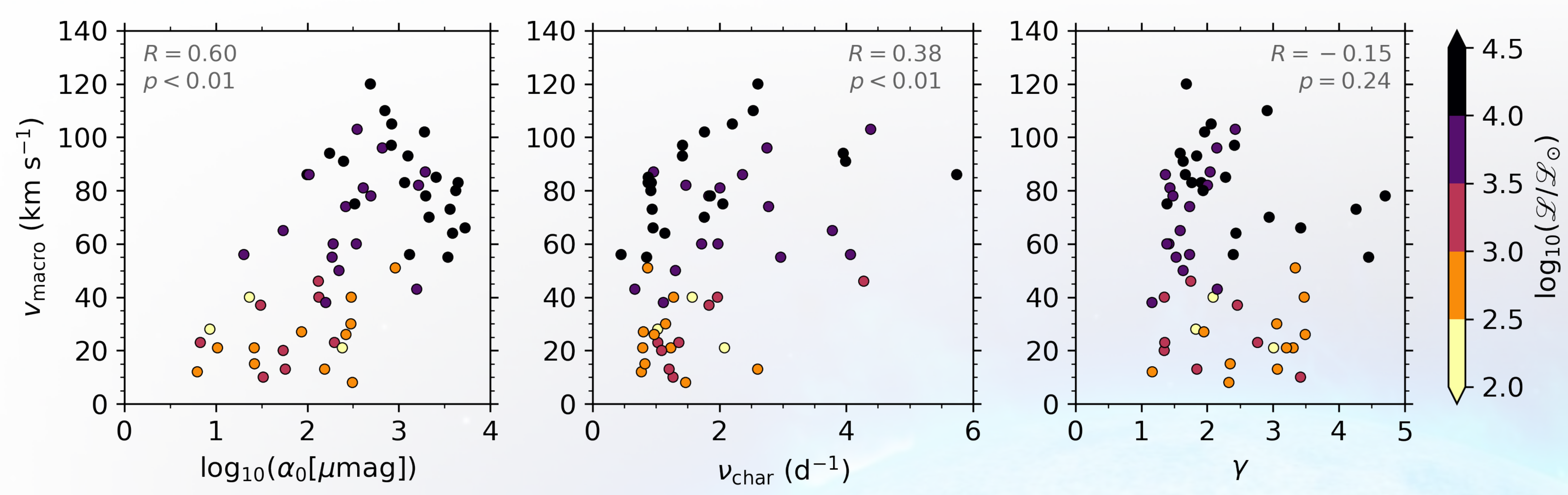

Figure 5: Correlation between IGW morphology and macroturbulence: more luminous stars have larger macroturbulence and higher amplitude IGWs.

Conclusions

- IGWs are **ubiquitous** in photometry of massive stars.
- Macroturbulence and the amplitude of IGWs are correlated: **IGWs are a plausible mechanism for macroturbulence**.
- Including **angular momentum transport** caused by IGWs is an important step in improving stellar evolutionary models.

Acknowledgements

The research leading to these results has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 670519: MAMSIE).

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