Massive Stars as Cosmic Engines
Proceedings IAU Symposium No. 250, 2007
F. Bresolin, P.A. Crowther & J. Puls, eds.

doi:10.1017/S1743921308020450

Can Pulsational Instabilities Impact a Massive Star's Rotational Evolution?

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Abstract. We investigate whether angular momentum transport due to unstable pulsation modes can play a significant role in the rotational evolution of massive stars. We find that these modes can redistribute appreciable angular momentum, and moreover trigger shear-instability mixing in the molecular weight gradient zone adjacent to stellar cores, with significant evolutionary impact.

Keywords. stars: early-type – stars: rotation – stars: oscillations – stars: variables: other – instabilities – waves – methods: numerical

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1. Background: Pulsation in Massive Stars

As the many, extensive variability surveys of the past couple of decades have revealed, pulsation in massive stars appears to be ubiquitous. Examples of these surveys include the *HIPPARCOS* astrometry mission, which photometrically discovered over a hundred new pulsating B stars (e.g., Waelkens *et al.* 1998); the study by Fullerton *et al.* (1996), revealing optical line-profile variations consistent with pulsation in 23 out of a sample of 30 O stars; and the *IUE* Mega campaign (Massa *et al.* 1995), which highlighted systematic variability in the wind of the early B supergiant HD 64760, subsequently attributed to co-rotating interaction regions rooted in photospheric pulsations (Fullerton *et al.* 1997; see also Kaufer *et al.* 2006).

Against this observational background, it seems reasonable to conjecture that those O and B stars already confirmed as pulsators could represent just the tip of the iceberg — that, in fact, a far greater proportion of massive stars are undergoing pulsations, albeit at amplitudes that fall below present-day detection thresholds. This expectation is lent considerable support by theoretical calculations (e.g., Pamyatnykh 1999, his Figs. 3 & 4) showing that any star with a mass $M_* \gtrsim 3\,\mathrm{M}_\odot$ *must* pass through one or more pulsation instability strips as it evolves from ZAMS to TAMS.

These instability strips all arise from the operation of a thermodynamic engine within the star, which converts radiant heat into mechanical energy associated with periodic pulsation. As Eddington (1926) originally pointed out ('*…we require, in fact, something corresponding to the valve-mechanism of a heat engine…*'), a key component of this engine is a regulatory process that adds heat to the stellar material when at its hottest, and removes heat when at its coolest. In classical (δ) Cepheid pulsators, the regulatory process is the positive temperature dependence of the Rosseland mean opacity κ at temperatures $\log T \approx 4.5$ where second helium ionization occurs. For massive pulsators, a similar 'κ mechanism' operates on the opacity peak at $\log T \approx 5.3$ associated with bound-bound transitions of iron-group elements. This 'iron bump' leads to overstable p-mode pulsations in the β Cepheid stars ($M_* \gtrsim 7\,\mathrm{M}_\odot$; Dziembowski & Pamyatnykh 1993), and to g-mode pulsations in the slowly pulsating B (SPB) stars ($3\,M_\odot \lesssim M_* \lesssim 7\,M_\odot$; Dziembwoski *et al.* 1993) and in supergiant B stars ($M_* \gtrsim 25\,M_\odot$; Pamyatnykh 1999). Here, the quoted mass ranges are for modes of harmonic degree $\ell = 0 \ldots 2$; toward larger values of ℓ, the SPB and supergiant g-mode instability strips merge (see Balona & Dziembowski 1999).

2. Wave Transport of Angular Momentum

Traditionally, massive-star pulsation has been regarded simply as a dynamical phenomenon to be modeled: we see variations in the photospheric or wind diagnostics of a particular star, and we attempt to interpret these variations as arising from pulsation perturbations. More recently, the advent of specialized space observatories such as *MOST* (Walker *et al.* 2003) and *COROT* (Baglin *et al.* 2006) has opened the door to applying the techniques of asteroseismology to massive stars — using the oscillation spectrum of a pulsating star to place constraints on interior physics such as the incidence of convective overshoot, or the degree of differential rotation.

In both of these contexts, pulsation is seen as a passive player in a star's evolution. But what if, conversely, the star's evolutionary trajectory were determined to some extent by its pulsation? This idea has already been applied to low-mass stars; Talon & Charbonnel (2003, 2005), for instance, argue that internal gravity waves (IGWs — essentially, g-mode transients damped over a timescale commensurate with their period) play a role in braking the rotation in the inner regions of such stars.

To include the effects of IGWs on stellar evolution, an extra term is added to the equation governing angular momentum transport, so that

$$\rho \frac{\mathrm{d}}{\mathrm{d}t}\left[r^2\Omega\right] = \frac{1}{5r^2}\frac{\partial}{\partial r}\left[\rho r^4 \Omega U\right] + \frac{1}{r^2}\frac{\partial}{\partial r}\left[\rho \nu r^4 \frac{\partial \Omega}{\partial r}\right] - \frac{3}{8\pi}\frac{1}{r^2}\frac{\partial}{\partial r}\mathcal{L}_J. \qquad (2.1)$$

This equation applies to shellular differential rotation (as argued by Zahn 1992, strong horizontal turbulence will tend to enforce uniform rotation across shells of constant radius r). Modulo geometrical factors of order unity, the term on the left-hand side represents the local rate of change of angular momentum per unit radius, with $\Omega(r)$ the local angular velocity. On the right-hand side, the first term represents angular momentum transport due to meridional circulation with a velocity $U(r)$. The second term represents diffusive processes with a transport coefficient ν; the major contribution to ν comes from convection and, in radiative zones, from secular shear instability (e.g., Maeder & Meynet 1996). Finally, the third term represents wave transport, as described by a luminosity function $\mathcal{L}_J(r)$ that quantifies the net amount of angular momentum carried per unit time through the shell at radius r. The main contribution to $\mathcal{L}_J$ comes from the Reynolds stress,

$$L_J = 4\pi r^2 \rho \langle r \sin\theta\, \mathbf{v}_r\, \mathbf{v}_\phi \rangle. \qquad (2.2)$$

Here, $\mathbf{v}_r$ and $\mathbf{v}_\phi$ are the radial and azimuthal velocity perturbations due to the wave, and $\langle\rangle$ denotes the average over all solid angles.

3. Application to Massive Stars

In low-mass stars, stochastic processes such as turbulent stresses or convective penetration are considered as the dominant wave excitation mechanism (e.g., Talon & Charbonnel 2003). Many authors have assumed that the same processes (albeit operating in different parts of the interior) are responsible for wave excitation in massive stars; for

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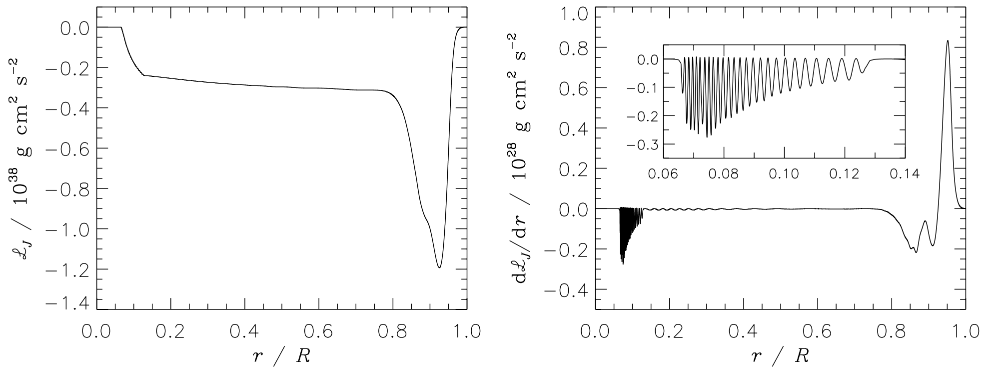

Figure 1. The angular momentum luminosity $\mathcal{L}_J$ (left), and its radial derivative $\mathrm{d}\mathcal{L}_J/\mathrm{d}r$ (right), plotted as a function of radius for the $\{n, \ell, m\} = \{40, 4, -4\}$ g mode of the $10\,\mathrm{M}_\odot$ model. The inset in the right-hand panel details the variation of the luminosity derivative in the μ-gradient zone adjacent to the core.

instance, Maeder & Meynet (2000) remark that '*... we could expect gravity waves to be generated by turbulent motions in the convective core.*'

However, as should be clear from §1, the waves observed in massive stars are not stochastic IGWs but unstable global standing oscillations, driven to large amplitudes by the iron-bump κ mechanism. Thus, the appropriate formalism for treating wave transport in these stars is a normal mode analysis with inclusion of excitation and damping processes — that is, nonradial, nonadiabatic pulsation theory. This was clearly recognized by Ando (1986, and self-references therein), who was the first to conjecture that nonadiabatic pulsation may play an important role in shaping the internal rotation profile of massive stars. Unfortunately, Ando's investigations predated the release (in the early 1990's) of updated opacity data that revealed the iron bump; thus, he was unable to reach any firm conclusions.

To build on this prior work, we examine angular momentum transport by high-order, intermediate-degree g modes in a $10\,\mathrm{M}_\odot$ stellar model near the end of its main-sequence evolution ($X_{\mathrm{core}} = 0.02$). (There is nothing particularly significant about this M_*; our results generalize to stars of both higher and lower masses. However, the late evolutionary stage is chosen to emphasize the deposition of angular momentum in the molecular weight gradient zone, discussed further below). We use the BOOJUM pulsation code (see Townsend 2005) to calculate the complex oscillation spectrum of the stellar model. Modes whose eigenfrequency ω has a negative imaginary part (i.e., $\Im(\omega) < 0$) are unstable; the eigenfunctions of these modes encapsulate all of the information necessary to evaluate the $\mathbf{v}_r$ and $\mathbf{v}_\phi$ terms in eqn. (2.2), with the exception of an arbitrary overall normalization.

Fig. 1 plots the angular momentum luminosity $\mathcal{L}_J$ as a function of fractional radius r/R_* for a single unstable g mode of the $10\,\mathrm{M}_\odot$ model, having indices $\{n, \ell, m\} = \{40, 4, -4\}$ and normalized so that the peak photospheric velocity perturbation is $1\,\mathrm{km\,s^{-1}}$ (this is a conservative choice; for reference, the typical photospheric velocities observed in pulsating massive stars are on the order of the sound speed, $\sim 10 - 20\,\mathrm{km\,s^{-1}}$). Also plotted is the luminosity derivative $\mathrm{d}\mathcal{L}_J/\mathrm{d}r$; as eqn. (2.1) indicates, this quantity is positive where angular momentum is extracted, and negative where it is deposited. The figure reveals angular momentum extraction from the surface layers, where the κ mechanism excites the g mode, and matching angular momentum deposition in the interior, primarily in two regions where the g mode is strongly damped. The outer damping region ($0.78 \lesssim r/R_* \lesssim 0.92$) arises from the κ mechanism operating in reverse: the opacity has

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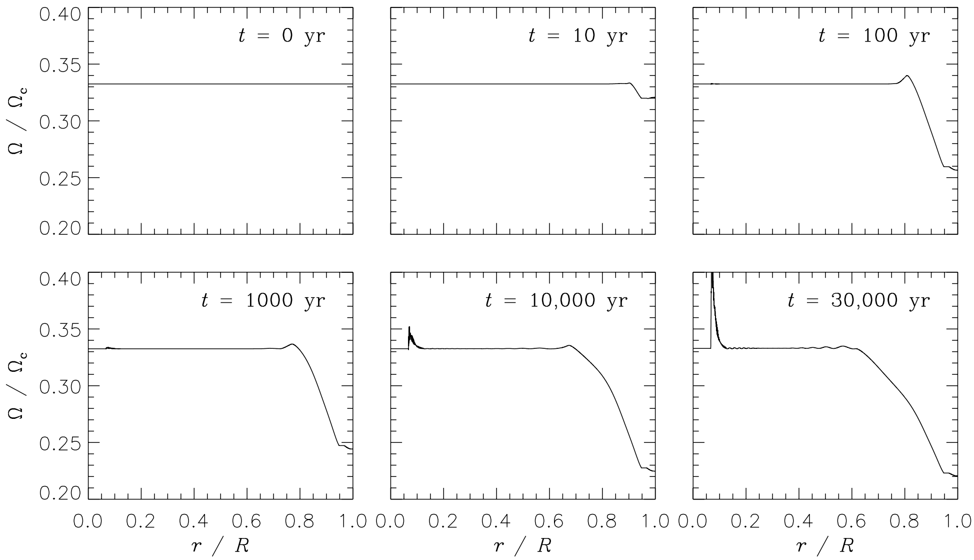

Figure 2. Snapshots of the angular velocity Ω of the $10\,\mathrm{M}_\odot$ model, plotted as a function of radius at six epochs during the HEIMDALL simulation.

a strongly negative temperature dependence, and so the thermodynamic engine converts mechanical energy into radiant heat. The inner damping region ($0.07 \lesssim r/R_* \lesssim 0.13$) is associated with the zone of varying molecular weight (μ) adjacent to the convective core. In this zone, the g mode has a very short wavelength due to the steep gravitational stratification; this leads to a spatially oscillatory pattern of angular momentum deposition, as can be seen from the inset in the right-hand panel of Fig. 1.

The angular momentum luminosity shown in Fig. 1 reaches a peak magnitude of $1.2 \times 10^{38}\,\mathrm{g\,cm^2\,s^{-2}}$; by way of comparison, Talon & Charbonnel (2003, their Fig. 4) find a net luminosity of $\sim 2 \times 10^{36}\,\mathrm{g\,cm^2\,s^{-2}}$ for IGWs in their model for a $1.2\,\mathrm{M}_\odot$ star. The two orders-of-magnitude difference between these values is simply a reflection of the far-higher amplitudes associated with the unstable modes found in massive stars, than the stochastically excited waves in low-mass stars. To give a rough estimate of the expected impact of the unstable modes, we note that over 1 Myr (a typical timescale for main-sequence evolution) the total angular momentum deposited in the μ-gradient zone by the $\{n, \ell, m\} = \{40, 4, -4\}$ mode would, *ceteris paribus*, be on the order of $8 \times 10^{50}\,\mathrm{g\,cm^2\,s^{-1}}$. This is approaching the total angular momentum $\sim 10^{51}\,\mathrm{g\,cm^2\,s^{-1}}$ stored in the core if the $10\,\mathrm{M}_\odot$ star were rotating uniformly at the critical rate. Thus, the angular momentum transport due to the pulsation can be expected to have an appreciable impact on the star's rotational evolution, and — at the most general level — the answer to the question posed in this paper's title is in the affirmative.

4. A Self-Consistent Simulation

Of course, the estimates given above neglect the fact that as the internal rotation profile evolves in response to the angular momentum transport, there will be a corresponding feedback effect on the pulsation. Clearly, some kind of self-consistent simulation is desirable, and to this end we have developed a prototype pulsation-transport code. The code, named HEIMDALL, solves the angular momentum transport equation (2.1) for an input

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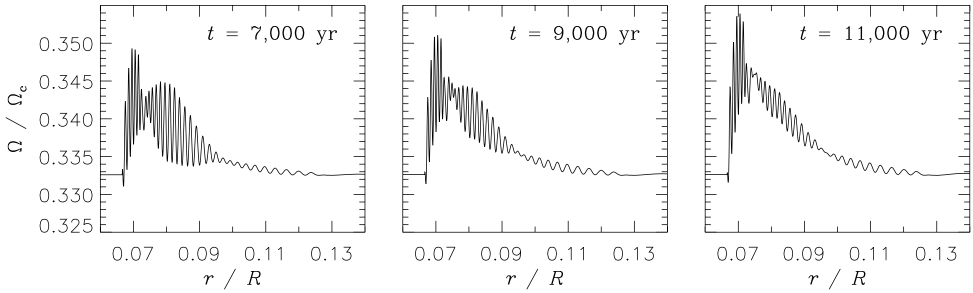

Figure 3. The evolution of the angular velocity Ω in the μ-gradient zone, for the same simulation shown in Fig. 2. Note how the steep shears in the left-hand panel have been mixed away by the shear instability in the center and right-hand panels.

stellar model. The meridional circulation term is neglected, because we are interested in transport occurring on timescales shorter than the circulation timescale R_*/U; however, the diffusion term is retained, to allow the rotation profile to relax from the steep angular velocity gradients created by the wave transport term. To evaluate the wave transport term, a modularized version of the BOOJUM code is used to calculate the complex oscillation spectrum of the stellar model at each simulation timestep. As in the preceding section, the angular momentum luminosity is obtained from mode eigenfunctions; however, rather than arbitrarily fixing mode amplitudes, HEIMDALL allows them to evolve over each timestep in accordance with individual linear growth/damping rates $-\Im(\omega)$.

Fig. 2 shows snapshots of the rotation profile $\Omega(r)$ for the $10\,\mathrm{M}_\odot$ model, from a HEIMDALL simulation of transport by $\{\ell, m\} = \{4, -4\}$ g modes. The simulation begins in a state of uniform rotation at 33% of the critical rate Ω_c. Initially, a broad spectrum of g modes, with radial orders $n = 26\ldots47$, are unstable toward the κ mechanism. As these g modes grow in amplitude, they transport angular momentum inwards from the surface layers. Because these layers contain little mass, they are braked quite rapidly; this established a broad shear region separating the interior from the surface, which acts to damp all but one of the initially unstable g modes. The radial order of the single remaining mode progressively increases from $n = 47$ to $n = 63$ in a sequence of mode-switching episodes; in between the switching, the mode hovers at the borderline of neutral stability, maintaining a surface amplitude of $\sim 1 - 2\,\mathrm{km\,s^{-1}}$.

In the $10,000\,\mathrm{yr}$ panel of Fig. 2, the long-term impact of the single remaining mode begins to emerge: angular momentum is deposited in the μ-gradient zone, resulting in its gradual spin-up. For the reasons discussed previously the deposition is spatially oscillatory, and leads to the establishment of nested shear layers of very narrow extent ($\sim 10^{-3}\,R_*$). These shear layers are clearly revealed in the left-hand panel of Fig. 3; however, in the center and right-hand panels, the shear layers have been partly dissolved by diffusive transport associated with the secular shear instability, which tends to smooth out steep gradients in Ω.

This result represents perhaps the most exciting finding in our exploratory calculations. As it dissolves shear layers established by pulsation angular momentum transport, the shear instability will mix the chemical composition in the μ-gradient zone. Given that this zone plays a pivotal role in modulating angular momentum transport, in particular serving as an insulator which inhibits meridional circulation coupling between core and envelope, *we expect that the disruption of this zone by shear/pulsation-assisted mixing (SPAM) will have a profound impact on the rotational evolution of massive stars.* Building

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on the foundation established by our HEIMDALL simulations, we plan further calculations to examine the precise nature of this impact.

Acknowledgements

RHDT is supported by NASA grant *LTSA*/NNG05GC36G.

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Discussion

CRANMER: Are your plots showing the equatorial plane? If so, might the angular momentum be circulating back toward the surface at mid-latitudes, say?

TOWNSEND: No, since the rotation is shellular, the angular velocity is uniform over each spherical surface.

MAEDER: [In considering angular momentum transport by g modes], if we account for horizontal turbulence, with the coefficient by S. Mathys and myself, it introduces a strong damping factor which considerably reduces the efficiency of this transport process.

TOWNSEND: I think that the horizontal turbulence will be efficient at damping IGWs excited stochastically in the core; but the g modes I'm considering are excited by the iron-bump κ mechanism in the envelope, and are far more robust. Don't forget that we see direct observational evidence for these unstable g modes.

SKINNER: Could you comment on what observational data are now available or might be available in the near future to test the validity of the models/simulations?

TOWNSEND: Survey data will be most useful in looking for evidence (e.g., a correlation between pulsation and surface enrichment) that the μ-gradient zone has been disrupted by SPAM. In this respect, both the Large Synoptic Survey Telescope and the Kepler mission look to be promising developments.