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Angular momentum transport by internal waves in the solar interior

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Abstract. The internal gravity waves of low frequency which are emitted at the base of the solar convection zone are able to extract angular momentum from the radiative interior. We evaluate this transport with some simplifying assumptions: we ignore the Coriolis force, approximate the spectrum of turbulent convection by the Kolmogorov law, and couple this turbulence to the internal waves through their pressure fluctuations, following Press (1981) and Garc a L opez & Spruit (1991). The local frequency of an internal wave varies with depth in a differentially rotating star, and it can vanish at some location, thus leading to enhanced damping (Goldreich & Nicholson 1989). It is this dissipation mechanism only that we take into account in the exchange of momentum between waves and stellar rotation. The flux of angular momentum is then an implicit function of depth, involving the local rotation rate and an integral representing the cumulative effect of radiative dissipation. We nd that the efciency of this transport process is rather high: it operates on a timescale of 10^7 years, and is probably responsible for the flat rotation prole which has been detected through helioseismology.

Key words: Hydrodynamics { turbulence { Sun: interior: rotation { stars: interiors: rotation

1. Introduction

Although it is well known that waves do carry momentum, this process has received little attention so far in stellar physics.The transport of angular momentum by internal waves (also called gravity waves) has been studied in the context of tidal braking involving massive binary stars (Zahn 1975a; Goldreich & Nicholson 1989), but only recently has it been invoked as a mechanism which could shape the rotation prole in the Sun (Zahn 1990; Schatzman 1993). In contrast, the importance of long ago in atmospheric sciences (cf. Bretherton 1969a,b): this phenomenon is responsible in particular for the so-called clear air turbulence.

The purpose of the present paper is to assess the efciency of angular momentum transport in a solar-type star, where such waves are generated by the turbulent motions of the convection zone. In this rst approach we shall make several simplifying assumptions, fully aware that the outcome must be considered as a crude approximation. The results may be easily transposed to massive stars, where these waves are emitted by the convective core.

The reason for examining the role of such waves in the Sun is that the other mechanisms which have been analyzed so far seem unable to achieve the flat rotation prole revealed by helioseismology (cf. Brown et al. 1989). Both rotation-induced turbulent diffusion (Endal & Soa 1978; Pinsonneault et al. 1989) and wind-driven meridian circulation (Zahn 1992) fail to extract sufcient angular momentum from the radiative interior (Chaboyer et al. 1995; Matias & Zahn 1996). Magnetic torquing looks at rst sight more promising, but the eld lines anchored in the differentially rotating convection zone would probably enforce non uniform rotation below (cf. Charbonneau & MacGregor 1993), and this is not observed.

We begin by recalling the main properties of the internal waves (Sect. 2), and calculate the flux of angular momentum carried by a monochromatic wave (Sect. 3). We then deduce the energy spectrum of those waves from their coupling with the turbulent motions at the base of the convection zone (Sect. 4) and integrate the angular momentum flux over the whole spectrum (Sect. 5). We nally derive an estimate for the efciency of the angular momentum transport by such waves in the Sun (Sect. 6) and end by some concluding remarks.

2. Properties of internal waves

The properties of internal waves propagating in stellar interi-