RING DIAGRAM ANALYSIS OF NEAR-SURFACE FLOWS IN THE SUN

SARBANI BASU
Institute for Advanced Study, Olden Lane, Princeton, NJ 08540

H. M. ANTIA
Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India

AND

S. C. TRIPATHY
Udaipur Solar Observatory, Physical Research Laboratory, P.O. Box 198, Udaipur 313 001, India

ABSTRACT

Ring diagram analysis of solar oscillation power spectra obtained from Michelson Doppler Imager data is carried out to study the velocity fields in the outer part of the solar convection zone. The three-dimensional power spectra are fitted to a model that has a Lorentzian profile in frequency and includes the advection of the wave front by horizontal flows in order to obtain the two components of the subsurface flows as a function of the horizontal wave number and radial order of the oscillation modes. This information is then inverted using the optimally localized averages method and regularized least squares method to infer the variation in horizontal flow velocity with depth. The average rotation velocity at different latitudes obtained by this technique agrees reasonably with helioseismic estimates made using frequency-splitting data. The shear layer just below the solar surface appears to consist of two parts, with the outer part measuring up to a depth of 4 Mm where the velocity gradient does not show any reversal up to a latitude of 60°. In the deeper part the velocity gradient shows reversal in sign around a latitude of 55°. The zonal flow velocities inferred in the outermost layers appear to be similar to those obtained by other measurements. A meridional flow from equator poleward is found. It has a maximum amplitude of about 30 m s⁻¹ near the surface, and the amplitude is nearly constant in the outer shear layer.

Subject headings: Sun: interior — Sun: oscillations — Sun: rotation

1. INTRODUCTION

The rotation rate in the solar interior has been inferred using the frequency splittings for p-modes (Thompson et al. 1996; Schou et al. 1998); however, the splitting coefficients of the global p-modes are sensitive only to the north-south axisymmetric component of rotation rate. To study the nonaxisymmetric component of rotation rate and the meridional component of flow, other techniques based on “local” modes are required. Since these velocity components are comparatively small in magnitude, they have not been measured very reliably even at the solar surface. The primary difficulty in measuring meridional flow velocities at the solar surface arises from convective blue shifts due to unresolved granular flows (Hathaway 1987, 1992). Additional difficulty is caused by the fact that at low latitudes the line-of-sight component of meridional velocity is small. Sunspots and other magnetic features have also been used to measure meridional flow (Howard 1996). There is a considerable difference in the results of these measurements. Using direct Doppler measurements at the solar surface from Global Oscillation Network Group (GONG) instruments, Hathaway et al. (1996) have measured various components of nearly steady flows on the solar surface. They find a poleward meridional flow with an amplitude of about 27 m s⁻¹, which varies with time. There is also some evidence for north-south difference in the rotation rate (Antonucci, Hoeksema, & Scherrer 1990; Verma 1993; Carbonell, Oliver, & Ballester 1993; Hathaway et al. 1996), but once again there is no agreement on the magnitude of this component or its statistical significance.

Apart from these nearly steady flows, there could also be cellular flows with very large length scales and lifetimes, viz., the giant cells. However, there has been no firm evidence for such cells (Snodgrass & Howard 1984; Durney et al. 1985), although recently Beck, Duvall, & Scherrer (1998) have reported probable detection of giant cells from the analysis of Michelson Doppler Imager (MDI) Dopplergrams. These large-scale flows are believed to play an important role in transporting magnetic flux and angular momentum, and thus their study is important for understanding the theories of solar dynamo and turbulent compressible convection (Choudhuri, Schussler, & Dikpati 1995; Brummell, Hurlburt, & Toomre 1998; Rekowski & Rüdiger 1998).

High-degree solar modes (l ≥ 150) that are trapped in the solar envelope have lifetimes that are much smaller than the sound travel time around the Sun, and hence the characteristics of these modes are mainly determined by average conditions in the local neighborhood rather than the average conditions over the entire spherical shell. These modes can be employed to study large-scale flows inside the Sun using time-distance analysis (Duvall et al. 1993, 1997; Giles et al. 1997), ring diagrams (Hill 1988; Patrón et al. 1997), and other techniques. Using time-distance helioseismology, Giles et al. (1997) have studied the meridional flow to find that the meridional velocity does not change significantly with depth, while Schou & Bogart (1998), using the ring diagram technique, found some increase in meridional velocity with depth. Ring diagram analysis of meridional flows have also been done by González Hernández et al. (1999) and Basu, Antia, & Tripathy (1999), who also found...