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Effects of alpha particles on the angular momentum loss from the Sun

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The classic Weber-Davis model, which treats the angular momentum loss of the Sun within the framework of MHD, is extended to incorporate alpha particles self-consistently. Closely following McKenzie et al. (1979), we exploit the fact that the ion gyro-frequency is many orders of magnitude larger than any other characteristic frequency in the ion momentum equation. This in effect requires all species flow along the magnetic field in a frame of reference corotating with the Sun. Governing equations are derived from standard transport equations in view of this alignment condition. The analysis is valid for general axisymmetrical flows where two major ion species have to be treated on an equal footing. As such, the model is also applicable to magnetized rotating stars other than the Sun. The governing equations are then solved on a prescribed meridional magnetic field line located at a colatitude of 70° at 1 AU. The general analysis concludes, in agreement with the Weber-Davis model, that the magnetic field helps to achieve an effective corotation out to the Alfvén radius, where the poloidal Alfvén Mach number M_T equals unity, provided that M_T is defined as a composite one. Model computations show that, even though the Poynting flux associated with the azimuthal components is negligible in the energy budget, the solar rotation nevertheless limits the ion differential streaming in the interplanetary space. Magnetic stresses predominate the angular momentum loss from the Sun. The proton contribution, which can be in excess of the magnetic one, is offset by the alphas that develop an azimuthal speed in the opposite sense to the solar rotation. For an alpha abundance compatible with in situ measurements, the azimuthal speeds of both protons and alphas far away from the Alfvén point are dominated by the differential streaming.