HYDRODYNAMICAL MODELS OF ROTATING MAGNETIC WINDS

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ABSTRACT. Numerical investigations of rotating stellar winds driven by a combination of magnetic and line radiation forces show a clear dichotomy: shallow winds have their azimuthal velocity enhanced by magnetic corotation, whereas steep winds may have a diminished circular velocity.

Limber (1974) and Saito (1974) amongst others have considered the nature of early-type stellar winds driven by magnetic corotation. These models were constructed before the development of modern radiatively driven wind theories, and also before the discovery of high ionization species (important for line driven winds) in Be envelopes. This paper reports some results of exploratory calculations which include the combined effects of both line radiation and magnetic forces on rotating stellar winds.

Attention is focussed on the equatorial plane of a steady-state isothermal spherically symmetric expanding rotating wind of infinite electrical conductivity and zero viscosity. It is supposed that magnetic field lines originating at the stellar equator are confined to the equatorial plane, so that a one-dimensional model may be constructed in that plane.

The azimuthal momentum equation and the centrifugal and magnetic terms in the radial momentum equation are treated according to the formalism of Weber and Davis (1967). In the radial equation, the force due to line radiation is represented through its dependence on the hydrodynamical density and velocity variables, in the manner derived by Castor, Abbott, and Klein (1975; CAK). The continuity and radial momentum equations are solved simultaneously by a Henyey relaxation code described in detail by Barker (1979), for a variety of combinations of parameters such as mass loss rate, stellar angular velocity, and photospheric radial field strength. Two sets of numerical calculations have been performed: one using an expression for the line radiation force such that the parent non-rotating non-magnetic wind accelerates steeply

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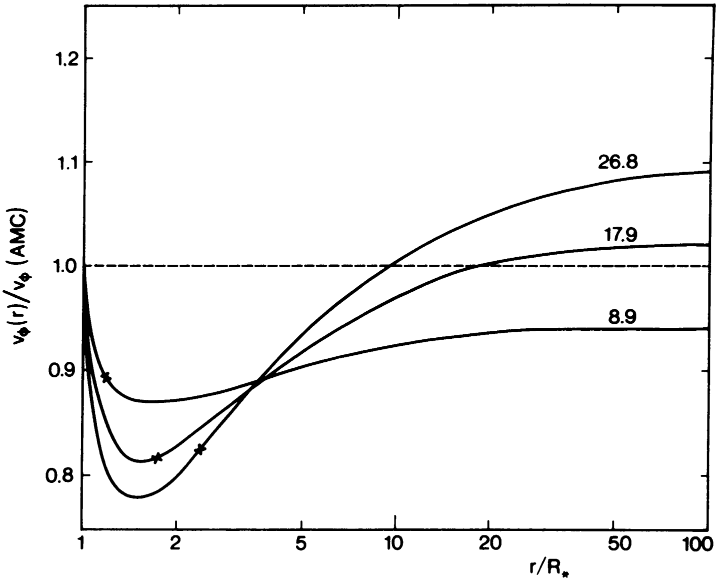

Figure 1. Azimuthal velocity vϕ in the equatorial plane of magnetic winds arising from a star of 13 M⊙ and 6 R⊙ rotating at 62% of the break-up velocity, with $\dot{M} = 5 \times 10^{-9}$ M⊙ yr^{-1}; vϕ is shown relative to the value from a non-magnetic 1/r conservation law. These models result from a hard (steeply accelerating) line radiation force law; curves are labelled with the photospheric radial field strength, and crosses mark the Alfvén radius.

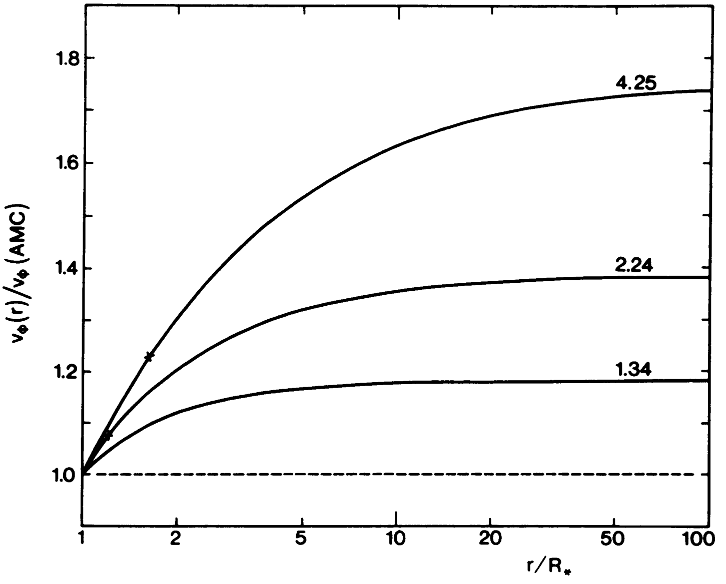

Figure 2. As in Figure 1, but for a semi-soft (gradually accelerating) line radiation force law.

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from the photosphere (a hard wind) as described by CAK; the second using a new expression for a gradually accelerating wind. The shallow wind form approximates the soft wind law of Abbott (1977) and is designated semi-soft as defined by Barker (1979).

The calculations were carried out in particular for a rapidly rotating B1V star with a Be-like mass loss rate of 5×10^{-9} $M_\odot$ yr^{-1}, and it was found that the hard and semi-soft winds respond in characteristically different ways to the effects of magnetic rotation. Thus far only extremely weak radial photospheric fields have been considered, with strengths far below the current observational limits of 1-200 Gauss (Landstreet, private communication) for Be stars.

In hard winds, the radial velocity law is not substantially affected by global radial stellar fields below 30 Gauss, but the azimuthal velocity is modified in a remarkable way. At small radii the circular velocity is reduced below the 1/r value corresponding to conservation of angular momentum in the fluid particles alone. Figure 1 shows the circular velocity in the hard magnetic winds--notice especially the sharp drop in v_ϕ (relative to 1/r) near the photosphere. This result is totally unexpected and is contrary to the prevalent intuitive picture that (by analogy with the solar wind) the rotation velocity in a stellar wind is necessarily enhanced by magnetic corotation.

Figure 2 shows the corresponding results for semi-soft winds. When the line radiation force produces gradual radial acceleration, the azimuthal velocity is indeed magnetically enhanced--by almost a factor of two even for exceedingly weak stellar field strengths. The radial velocity structure is also appreciably modified in these winds.

Numerical difficulties were formidable even for the current weak-field models; development of the code is in progress to investigate the cases of stronger magnetic fields and higher rotation rates.

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DISCUSSION

Endal: Is the effective moment-arm of your winds given by the radius at the Alfven point, as in the Weber-Davis solar wind model?

Barker: The Weber and Davis theory is formally correct only in the case of zero photospheric mass loss. These calculations were performed using a corrected version of the theory, in which the solar-wind result you quote is no longer valid.

Harmanec: Could you estimate how strong the magnetic field must be to obtain detectible difference between magnetic and non-magnetic wind?

Barker: Even 5 Gauss fields have substantial effects on the wind velocity structure; calculations are planned to investigate the resultant observable line profile changes.