COMMENTS

L. MESTEL
(Dept. of Mathematics, University of Manchester, U.K.)

I would like to make a few comments, relevant to different points raised in the Discussion.

(i) When discussing stellar angular momentum, we should remember that substantial magnetic braking is likely during contraction towards the main sequence in both the Hayashi and post-Hayashi phases, for we have every reason to expect a strong stellar wind. Even if the star has earlier lost most of its primeval magnetic flux, it is plausible that there will be a dynamo-generated field, as in the solar atmosphere, able to control the gas flow out to radii well beyond the stellar surface, and leading to a considerable increase in the amount of angular momentum carried away for a given loss of mass. (In fact, numerical computations suggest the possibility that a star which *has* retained a strong primeval field does not necessarily lose more angular momentum than one with only a dynamo-driven field, but rather that the same amount of braking is achieved for a much smaller mass loss.) The point is that I do not think one can strictly describe any star in these phases as 'non-magnetic', following its rotational evolution without feeling any magnetic torque. In particular, it is not clear that stars contract in a state of close balance between centrifugal force and gravity at the photospheric equator, as assumed by Dr. Roxburgh: magnetic braking *may* always be efficient enough to keep the ratio well below unity, in spite of the contraction.

(ii) I had expected that Dr. Huang would discuss the model that he and I have independently put forward for the formation of close binary main-sequence systems, using magnetic braking. Basically, the idea is that if a pair of coupled proto-stars are each losing angular momentum of spin, but if there is strong spin-orbit coupling, tending to synchronize periods of rotation and revolution, then the loss of spin angular momentum will be made up at the expense of the orbital angular momentum, and the two stars will approach each other, remaining a close binary system in spite of their contraction by large factors to their main-sequence states.

Although I still like this picture, I want to point out a possible difficulty. We want to apply the braking theory both to individual stars – explaining at least semi-quantitatively the distribution of angular momentum along the main sequence – and to double stars. The danger is that if the process works at about the right efficiency for single stars, it will not be efficient enough for the double-star problem; whereas if the double-star process works adequately, then the same theory applied to single stars will yield main-sequence rotation periods that are far too long. The difficulty may be avoi-

Perek (ed.), Highlights of Astronomy, 453–454. © *I.A.U.*

ded, however, if the rate of magnetic braking depends in a *non-linear* way on the instantaneous angular velocity, so that the process works at maximum efficiency only when centrifugal force is close to gravity. This will be the case when the stellar wind is a 'centrifugal' rather than a thermal wind, with the mass and angular-momentum loss decreasing sharply as the centrifugal forces decrease.

(iii) The classical process of spin-orbit synchronization is 'tidal friction' – the continuous destruction of the energy of the tidal motions set up within the components of a non-synchronized binary system. But tidal friction decreases like the sixth power of the mutual separation of the two components, and so may not always be efficient enough, even when the friction is due to eddy viscosity in a largely turbulent star. However, a magnetic star tends to keep its corona co-rotating with the bulk of the star. In a non-synchronized binary system there will result violent shearing motions in the common corona; if these motions become turbulent, there may be enough dissipation to maintain nearly synchronous motion.

(iv) In connection with Dr. Van den Heuvel's contribution: accepting the strong correlation between the Am (and possibly also the Ap) characteristic and membership of close binary systems, perhaps we should look upon binary membership in this context not as a primary phenomenon, but rather as the cause of *slow rotation*, through spin-orbit coupling. (Normal A stars rotate rapidly, and Dr. Abt has remarked that those A stars that are found in wide long-period binaries where spin-orbit coupling is weak do have normal spectra.) If we associate the Am or Ap characteristic with the presence of a photospheric magnetic field, the problem reduces to explaining why slowly rotating stars have strong *surface* magnetic fields. The reason may be that in rapidly rotating stars the Eddington-Sweet circulation flows and drags the field lines beneath the surface; but in a slowly rotating, strongly magnetic star, thermal equilibrium is achieved without any meridian circulation, and the field lines appear above the surface.

(v) Finally, taking up Dr. Huang's and Dr. Batten's remarks on the orientation of stellar angular-momentum vectors, again I would like to emphasize that a lot happens in between formation of a protostar and its arrival on the main sequence. In particular, if the angular-momentum vector and the magnetic dipole are neither parallel nor perpendicular, the net couple on the star due to a stellar wind will be inclined to the angular-momentum vector, and so will not only brake the star, but will also rotate the angular-momentum vector. It is hoped that further computations will show whether the tendency is to align the angular momentum and magnetic dipole, or to make them perpendicular. Meanwhile, it seems premature to draw firm conclusions about the processes of protostar formation, though I agree that the vorticity associated with the turbulence in gas clouds must be included along with that due to the overall galactic rotation.