MAGNETIC BRAKING, THE SOLAR NEBULA AND THE COMETARY CLOUD

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Biermann (1979) has revived the earlier suggestion of Cameron and of Donn that the proto-cometary cloud and the proto-solar nebula were contiguous but distinct cloudlets, forming e.g. as fragments within the same massive interstellar cloud. As in Goldreich and Ward (1973) and Biermann and Michel (1978), the cometesimals are thought to have formed in a layer of dust that settled in the equator of a cloudlet maintained at a moderate density by a combination of thermal pressure and centrifugal force due to a high angular momentum. The solar nebula had much less angular momentum and so could contract to about the radius of Pluto's orbit before achieving centrifugo-gravitational balance. In this paper it is noted that modest variations in the initial parameters of fragments forming within the same massive magnetic cloud can yield both high and low angular momentum cloudlets (Mestel and Paris 1979). A fragment of mass M greater than a critical mass M_c, defined in terms of its magnetic flux F by $GM_c^2 \sim F^2/\pi^2$, contracts in approximate mechanical equilibrium, at the rate determined by the magnetic transport of angular momentum, and with centrifugal force remaining comparable with gravity. Rapid flux-loss at molecular cloud densities leaves a weakly magnetic, rapidly rotating, low-density cloudlet which could be the locale of cometary formation. If $M<M_c$, the magnetic stresses both limit contraction and enforce corotation with the surroundings. As flux leaks out slowly, the cloudlet contracts in approximate magneto-gravitational equilibrium, with centrifugal forces becoming a steadily smaller fraction of gravity. At the molecular cloud phase, rapid flux-loss leaves now a slowly rotating cloudlet, which can therefore become the proto-solar nebula. Whether a cloudlet is super- or sub-critical in mass will depend on the details of the fragmentation process in the parent cloud, in particular on the amount of mass agglomeration down the field-lines.

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DISCUSSION

Mouschovias: It is certainly proper to study magnetic braking for a wide range of values for the free parameter(s) (e.g., M/M_{crit}). It is, however, fair to point out that actual physical conditions in the interstellar medium are such that, for densities less than a few x $10^3 cm^{-3}$, the free fall time is longer than the characteristic time for magnetic braking. Since, as I explained in my review, even observations of rapidly rotating, dense clouds show that the bulk of the angular momentum problem has been resolved by the time the density has reached about $10^4 cm^{-3}$ and since individual cloud masses are relatively small, it is $M/M_{crit} < 1$ which is relevant. Your statement about solutions for $M > M_{crit}$ could apply only to the later, denser ($> 10^4 cm^{-3}$) phases of cloud contraction; in these stages, only a relatively small additional amount of angular momentum need be removed.

Mestel: A time of magnetic braking must refer to the mass that is being braked. I presume you mean that most of the actual clouds observed today are of sub-critical mass, and so are magnetically-supported long enough for effective corotation with the surroundings to be maintained. However, one can still speculate about a massive magnetic cloud, from which the proto-solar nebula and possibly the proto-cometary cloud condensed and with different parameters. There may also be an observational selection effect; clouds with $M > M_{crit}$ may be hard to find since they contract as they lose angular momentum and presumably fragment.

Kippenhahn: In order to avoid the impression that all work on rotation is worthless if there is the slightest magnetic field present, I would make the following remark. We observe effects in chemical abundances which can be explained by circulation caused by rotation. We hope to see whether this is the only possible explanation and use it as a test for the existence of circulation. But even if there are magnetic fields in all stars, it is important to know what kind of topology they have. One could think of complicated flow patterns which can change the topology of the fields separating the very interior from the outer regions. Only if you have magnetic field lines which connect the surface with the central regions is there transport of angular momentum from the central region outwards. I think it would be too simple to assume that whenever there is a magnetic field we have uniform rotation (or solid body rotation), and all the meridional circulation is suppressed.

Mestel: I did not imply that the magnetic field must suppress meridional circulation. On the contrary, I think that moderately strong fields keep the Eddington-Vogt-Sweet circulation going, by offsetting the advection of angular momentum. However, in singular regions it may no longer be consistent to ignore magnetic effects on hydrostatic, and so also on radiative, equilibrium. I agree that the detailed structure of the magnetic field is often crucial, and steady detachment of the field-lines of a contracting core from the expanding envelope will slow the outward transport of angular momentum. But, again, the long time-scale of normal stellar evolution works in favour of isorotation.

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