CONCLUDING SUMMARY REMARKS

L. Woltjer
European Southern Observatory
Karl-Schwarzschild-Str. 2, D-8046 Garching b. München, F.R.G.
and
Observatoire de Haute Provence
F-04870 Saint-Michel l'Observatoire, France

Fifty years ago at a conference on the structure of galaxies almost everything would have been ascribed to gravity. A decade later turbulence became the new thing - partly to solve angular momentum problems. Again a decade later magnetic fields followed: synchrotron radiation was observed, angular momentum could be efficiently transported and a variety of bizarre extragalactic shapes was thought to be related to magnetic fields. In the sixties, however, the situation was reversed when it turned out that spiral structure could perhaps be understood on a gravitational picture with some simple hydrodynamics and that some of the most intriguing shapes could be reproduced in simulations of the gravitational interaction between galaxies. As a consequence magnetic fields again diminished in importance. The next decade saw a much increased role for the thermodynamics of the interstellar medium. At the end of this meeting it is clear that while gravity, hydrodynamics and thermodynamics are important, magnetic fields cannot be neglected and should be integrated into the overall picture.

Much progress has been reported on measurements of galactic magnetic fields - largely due to improved receivers and data processing rather than to new telescopes. The Zeeman and Faraday effects yield values for

$$\int n_a \ \mathbf{B} \cdot d\boldsymbol{\ell} \tag{1}$$

with a standing for H, OH ... CCS (or some particular atomic or molecular state of these) for the former and for electrons for the latter. The synchrotron radiation ($F_\nu \propto \nu^\alpha$) yields

$$\int n_{CR^-} \ B_\perp^{1-\alpha} \ d\boldsymbol{\ell} \tag{2}$$

with n_{CR^-} the density of cosmic ray electrons, and a somewhat more complex expression for the polarization. Finally, optical polarization also gives some information about the mean field direction. The interpretation of measurements of these integrals is not always simple. In (1) regions of opposite field cancel and in particular small scale fields may

escape detection, while in both (1) and (2) possible (anti)correlations of n and B may influence the results.

There seems to be agreement now that in a typical volume of interstellar space there is a regular field of a few μG - with probably a random component of the same order. In spiral arms the polarization of synchrotron radiation is frequently low and random fields may be important, while at large distances from a galactic plane there is some predominance of fields in the radial or in the z-direction, though the polarization is relatively modest. Far out in the disk in interarm regions, the fields appear to be more regular with polarizations of up to 60 percent. One may wonder whether such fields could be dynamically important in the tenuous outer parts of galaxies and affect the interpretation of the rotation curves with their implications for dark matter.

In molecular clouds the fields are stronger (perhaps with $B \propto \rho^{1/2}$); in OH masers a few mG are reached and in H_2O masers ten times as much. The dynamic effects of such strong fields may be of dominant importance, as may be their role in star formation.

Concerning the overall structure of the magnetic fields in galaxies, evidence has been presented for axisymmetric structures in some and bisymmetric structures in others. Our own Galaxy could be of the latter kind since somewhat inside the solar orbit the field seems to change sign; more complex structures cannot be excluded. The most unambiguous data on the field structure in our Galaxy come from Faraday effect measurements in pulsars, obtained as a by-product of pulsar studies. Perhaps a pulsar survey specifically optimized for elucidating the field structure in our Galaxy would be worthwhile.

The origin of the magnetic fields still poses problems. Much progress has been reported here on dynamo theory with a certain correspondence between predicted and observed field shapes. The way in which the field strength is determined still is very unclear. Some kind of seed field is also needed for dynamo amplification, and it has been suggested that this could be of cosmological origin or that it could be derived from supernova remnants. Since the fields in SNR may have very many reversals it is perhaps not evident that there is enough time available to organize them into a large scale galactic field. If this could be done it could lead to an attractive picture in which stellar and galactic dynamos would be coupled as follows:

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┌──────────────────┐   ┌──────────────────┐   ┌──────────────────┐
│  STAR FORMATION  │──▶│ STELLAR DYNAMO   │──▶│    STELLAR B     │
└──────────────────┘   └──────────────────┘   └──────────────────┘
         ▲                                              │
         │                                              ▼
         │                                     ┌──────────────────┐
         │                                     │     PULSAR B     │
         │                                     └──────────────────┘
         │                                              │
         │                                              ▼
┌──────────────────┐   ┌──────────────────┐   ┌──────────────────┐
│    GALACTIC B    │◀──│ GALACTIC DYNAMO  │◀──│ SUPERNOVA REMN B │
└──────────────────┘   └──────────────────┘   └──────────────────┘
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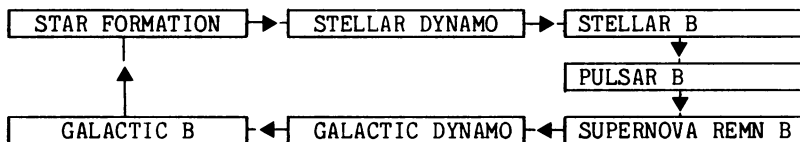
However, before we give too much credence to the various schemes, it might be good if we arrived at a full quantitative understanding of the solar dynamo, which owing to the much tighter observational constraints still appears to have many uncertain aspects.

MOUSCHOVIAS: I have a comment on two points made by Dr. Woltjer in his concluding remarks.

(1) On the agreement between observations and our prediction B $\propto \rho^{1/2}$ in self-gravitating clouds, he said that everything looks better on a log-log plot. That's certainly so but when, as in the case of the latest Myers et al. OH Zeeman measurement, we predict (given the mass and density of the cloud and the ≈ 3 μG background field) a field strength of 28 μG and the measurement is 27$\pm$4 μG, this excellent agreement between theory and observation will not go away no matter what kind of axes labels one uses to display it.

(2) Dr. Woltjer also referred to "hand-waving arguments" relating to ambipolar diffusion in molecular clouds. I would like to believe that he was not referring to our work. Here I have a transparency showing the full two-fluid MHD equations which we solve in our studies of the collapse of self-gravitating clouds, properly accounting for ambipolar diffusion. (These are the same as the vectorial equations given in Paleologou and Mouschovias (1983, Astrophys. J. **275**, 838).) The calculations I reported on are as rigorous as they can ever be; there is nothing hand-waving about them. So, unless somebody points to an invalid assumption we made or to a mathematical error in our solutions, one has no choice but to accept our results on when and how the magnetic field decouples from the matter and on how much the flux-to-mass ratio of the cloud's core is reduced by ambipolar diffusion. That, I believe, is the way of science.

MESTEL: May I re-emphasize that although the galactic magnetic field plays a major role in contemporary star formation, in particular in connection with the angular momentum problem, I think it is too early to assert that stars could not form in the absence of a magnetic field. Several workers are studying the effects of gravitational torques in non-axisymmetric, non-magnetic systems. One looks forward to the different theories being developed to the point. Wrong comparisons can be made of their predictions, e.g. of the zero-age main sequence mass spectrum.

BELVEDERE: I would like to add a comment on the dynamo: As a theorist who has some expertise in stellar dynamos, I would point out that the magnetic field should be relevant as to consistently determine the structure and dynamics of models of accretion disks onto compact objects. But, on the other hand, one must be careful in extending what we know about stellar dynamos to other astrophysical systems since, even in the case of the Sun, several questions are still open, primarily the location of dynamo action in the Sun's interior and the driving mechanism (radial or latitudinal differential rotation).

WIELEBINSKI: The question of poloidal fields in galaxies should be strengthened. An increasing body of observational evidence is now coming together (e.g. M82, M104, NGC 1808, etc.). All these galaxies have a poloidal field and a CO ring rotating around the nucleus.

Boat trip on river Neckar (M. Fujimoto and L. Woltjer)

Excursion to Bad Wimpfen (C. Heiles, T.Ch. Mouschovias and R.M. Kulsrud)