Chapter 7

Conclusion

7.1 Summary

The generation of coherent magnetic fields on scales exceeding the scale of turbulent motions in astrophysical objects, is studied within the realm of the Mean-Field Dynamo (MFD) theory. The technical tools made available by the MFD theory has motivated much of the research in this field over the past few decades. But a host of conceptual problems in the theory still remain to be circumvented. In this thesis, we have addressed some of these potential problems. In addition, we have also examined the possibility of large-scale dynamo action arising from effects other than the ones in the conventional mean-field dynamo paradigm.

We began by examining the issue of dynamo coefficients in the kinematic regime for large magnetic Reynolds number ($R_m$). Here we used direct numerical simulations of helically forced turbulence to determine the $\alpha$-effect and the turbulent magnetic diffusivity $\eta_t$, using the Test-field method. We find that for isotropic, homogeneous turbulence, the high conductivity results obtained under closure approximations like FOSA agree reasonably with the dynamo coefficients obtained numerically up to moderate values of $R_m \sim 220$. It is worth noting that this agreement between the theoretical and numerical values is obtained even in the presence of an exponentially growing small-scale field $b$ due to the fluctuation dynamo. We also find that the dynamo coefficients are independent of $R_m$ in the regime $R_m > 1$. Extension of these results to even higher $R_m$ values is essential but even at this level, it is clear that the dynamo coefficients are indeed related to the statistical properties of the turbulent flow and are consistent with analytical results that are based on simple closure hypothesis.
We then investigated in Chapter 3, the effect of nonlinear backreaction on these transport coefficients. This is important in order to gain insight about the nature of the saturation behavior of large-scale dynamos. Using an exactly solvable model of nonlinear dynamos in the limit of small fluid and magnetic Reynolds number, we have shown explicitly that the $\alpha$-effect can be expressed either completely in terms of the velocity field as in traditional FOSA or it can be expressed as a sum of two terms, a so-called kinetic $\alpha$-effect and an oppositely signed term proportional to the helical part of the small-scale magnetic field. These results reconcile apparently conflicting viewpoints expressed by several authors. The growing small-scale current helicity associated with the small-scale field gradually suppresses the total $\alpha$-effect, eventually leading to the quenching of the dynamo. The inclusion of magnetic helicity fluxes which can allow for the removal of the small-scale magnetic helicity could then ensure healthy dynamo action.

Numerical solutions obtained by solving galactic dynamo equations including different kinds of magnetic helicity fluxes indeed support the above mentioned idea. In fact, our results for an advective flux of helicity shows that even for moderate advection, the dynamo can recover from catastrophic quenching and ultimately lead to steady large-scale magnetic fields of strengths of about a fraction of the equipartition field strength. Advective flux of helicity aided by a flux arising from the anisotropy of turbulence and shear (Vishniac-Cho flux) further aids the dynamo to grow stronger large-scale fields. For stronger shear, the Vishniac-Cho flux is capable of alleviating dynamo quenching even when the advection is so strong that it removes both the large- and small-scale magnetic fields. The utility of the Vishniac-Cho flux is also evident in the absence of the advective flux. In this case, it was found that for strong shear, this flux can by itself help the dynamo to survive catastrophic quenching and lead to strong fields, albeit requiring a strong initial seed field.

In the light of potential problems with the coherent $\alpha$-effect, it is also important to explore other mechanisms for generating large-scale magnetic fields. One such possibility is whether random fluctuations in the kinetic $\alpha$-effect about a zero mean value combined with shear can generate large-scale magnetic fields. This was examined using two different types of probability distribution functions (PDF's) for the stochastic $\alpha$. One of them was similar to Sokoloff (1997) model while the other one was a Gaussian PDF. Using a one-dimensional model of galactic dynamos, we find that the net growth or decay of the field depends not only on the dynamo parameters but also on the particular realization, the correlation time of
The stochastic $\alpha$ compared to turbulent diffusion timescale and the time over which the system is evolved. For small correlation times, a stochastic $\alpha\omega$-dynamo can lead to growth of the magnetic field for a few turbulent diffusion times even for $|D| \sim 40$. But a much larger $|D| \sim 160$ is required for growth over long time scales. For dynamos where both a coherent and fluctuating $\alpha$ are present, the stochasticity of $\alpha$ can help alleviate catastrophic dynamo quenching, even in the absence of helicity fluxes. One can obtain final field strengths up to a fraction $\sim 0.01$ of the equipartition field $B_{eq}$ for dynamo numbers $|D| \sim 40$, while fields comparable to $B_{eq}$ require much larger degree of $\alpha$ fluctuations or shear. This type of dynamo may be particularly useful for amplifying fields in the central regions of disc galaxies.

Magnetic fields on scales larger than the scale of the flow could also arise from flows having a net cross helicity. Investigating one such non helical flow (Archontis flow) through direct numerical simulations, we demonstrated that the mean emf due to the cross helicity effect is proportional to the mean magnetic field and can hence lead to exponential amplification of the field for $R_m$ above a certain critical value. But the saturation behavior of a cross helicity driven dynamo differs significantly from the conventional $\alpha^2$ dynamo. For such simple flows, we find that the crucial factor that leads to net cross helicity production is the correlation between the driving force and the mean-field. The generated cross helicity along with large-scale vorticity then contributes to the mean emf giving rise to a large-scale dynamo.

We now turn to possible future directions of the work presented in the thesis.

### 7.2 Future directions

The research themes presented in this thesis highlighted some of the potential problems associated with the dynamo generation of large-scale magnetic fields in astrophysical objects. We have tried to address these problems using both analytical as well as numerical techniques. In the following, we highlight in brief some possible extensions of the work related to this thesis.

In this thesis, we have studied the possibility of galactic dynamo action driven by a stochastic $\alpha$-effect in association with shear. Our results pointed out the interesting features of a stochastic $\alpha\omega$-dynamo and it's ability to alleviate catastrophic $\alpha$-quenching. However, these investigations were only restricted to a stochastic $\alpha$-effect random in time but uniform in space. Extending the existing setup to studying the effects of spatial decorrelation on the galactic dynamo is an important
7.2: Future directions

problem. In addition, we would also like to explore whether additive noise (produced by small-scale dynamo action) in combination with shear can aid dynamo action (c.f Blackman (1998)).

Spiral galaxies are known to possess large-scale magnetic field. The magnetic field is usually assumed to be frozen into the plasma and respond directly to any rapid changes in gas density. Due to this, the galactic magnetic field is naively expected to be stronger in the gaseous spiral arms where the gas density is enhanced. But in some galaxies, most noticeably in NGC 6946 (Beck & Hoernes, 1996) observations show the presence of magnetic arms located between the gaseous spiral arms. This is contrary to the strong correlation expected between the large-scale field and the ambient gas density. We plan to investigate this problem further with the aim to explore whether new mean-field effects and account for such observed phenomena. For example, a promising idea to explain such a phenomena would be to include a time derivative of the mean-field in the expression for the mean emf $\mathcal{E}$. This could be motivated either from FOSA and MTA. Such a term will lead to a telegraph type mean-field equation allowing for wave-like solutions of the disc dynamo equations.

In the context of galactic dynamos, we intend to further develop our models of galactic dynamo driven by helicity fluxes with the purpose of establishing the dependence of the magnetic field parameters (strength, scale, growth rate and time, symmetry in the vertical and azimuthal directions and spiral patterns) on the observable parameters of galaxies such as the rotation curve, gas density, star formation rate and the possibility of galactic wind or fountain flows. For this, we plan to extend our one-dimensional galactic dynamo code to include radial and azimuthal directions and explore the above connections. We expect that this will allow not only a better understanding of the origin of galactic magnetic fields, but will also provide a better understanding of the evolution of galactic magnetic fields over cosmological time scales.

We plan to address some of the above issues in future.