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The Origin of Magnetic Fields in Elliptical Galaxies

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Abstract. We argue that interstellar gas in elliptical galaxies can be turbulent, with turbulent scale and velocity of 400 pc and $20\,\mathrm{km\,s^{-1}}$ respectively. An upper limit on turbulent velocity, $\simeq 50\,\mathrm{km\,s^{-1}}$, follows from the requirement that the turbulence dissipation rate does not exceed the X-ray gas luminosity. The turbulence can generate random magnetic fields of $0.3\,\mu$G strength at the above scale via fluctuation dynamo action. The resulting Faraday rotation is random, with a typical value of 5–$30\,\mathrm{rad\,m^{-2}}$, consistent with observational evidence available.

1. Introduction

The stellar population of elliptical galaxies is old and the interstellar gas is dilute (Fabbiano 1989). Therefore, both relativistic and thermal electrons have low density, and any synchrotron emission and Faraday rotation can only be weak. Nevertheless, there are several lines of evidence, albeit mostly indirect, suggesting significant magnetic fields in ellipticals (Moss & Shukurov 1996; Mathews & Brighenti 1997). The magnetic field should be random, producing unpolarized synchrotron emission and fluctuating Faraday rotation. The r.m.s. Faraday rotation measure attributable to the ISM of the ellipticals is $\langle \mathrm{RM} \rangle = 5$–$100\,\mathrm{rad\,m^{-2}}$.

2. Turbulent interstellar gas in elliptical galaxies

Interstellar gas in elliptical galaxies is observed via its X-ray emission (Fabbiano 1989). Type I supernovae (SNe) (and also stellar winds and random motions of stars) heat the gas to the observed temperatures $T \simeq 10^7\,\mathrm{K}$. It is natural to expect that a fraction ϵ of the energy is converted into turbulent motions of the gas (Moss & Shukurov 1996; Mathews & Brighenti 1997). The turbulent scale $l \simeq 400\,\mathrm{pc}$ is given by the diameter of a SN as it reaches pressure balance with the ambient medium whose typical density is $n \simeq 10^{-3}\,\mathrm{cm^{-3}}$. The balance between energy injection and dissipation rates yields a turbulent velocity of $v \simeq 20\,\mathrm{km\,s^{-1}}$ for $\epsilon = 0.1$, assuming the energy dissipation time $\tau \simeq l/v$ as for Kolmogorov turbulence. This estimate of v is compatible with the constraint $v \lesssim 50\,\mathrm{km\,s^{-1}}$ resulting from the observed X-ray luminosity. Another driver of turbulence is the random motions of stars. These generate random vortical motions at a smaller scale and velocity, $l_* \simeq 3\,\mathrm{pc}$ and $v_* \simeq 3\,\mathrm{km\,s^{-1}}$, respectively (Moss & Shukurov 1996).

The driving force produced by an expanding quasi-spherical SN remnant is potential. The above estimates assume that the motions driven by the SNe are vortical, so $\tau = l/v$ applies. In spiral galaxies, the potential (acoustic) motions are efficiently converted into vortical turbulence mainly due to the inhomogeneity of the ISM. The ISM in elliptical galaxies is hot and, presumably, rather homogeneous at kpc scales. Therefore, Moss & Shukurov (1996) suggested that SNe will drive sound-wave turbulence whose correlation time τ is $(v/v_s)^{-2} l/v_s \simeq 3 \times 10^7$ yr rather than l/v, where $v_s \simeq 300\,\mathrm{km\,s^{-1}}$ is the speed of sound. However, Mathews & Brighenti (1997) noted that sound waves quickly dissipate, and so cannot form a pervasive turbulent velocity field. The nature of turbulence in elliptical galaxies needs to be studied further.

3. The fluctuation dynamo

Random motions can act as a dynamo, generating random magnetic field, if the magnetic Reynolds number R_m exceeds a critical value $R_\mathrm{m,cr} \simeq 100$ (Zeldovich, Ruzmaikin, & Sokoloff 1990). As in most astrophysical objects, R_m in elliptical galaxies by far exceeds $R_\mathrm{m,cr}$, so fluctuation dynamo action in ellipticals is quite plausible. The e-folding time of the random field in a vortical random flow is of the order of the eddy turnover time, $\tau = 2 \times 10^7$ yr. The magnetic field is concentrated into flux ropes whose length and thickness are of order $l \simeq 400$ pc and $l R_\mathrm{m,cr}^{-1/2} \simeq 40$ pc (Subramanian 1999). In the ropes, the magnetic field is plausibly in equipartition with the turbulent kinetic energy, $b \simeq 0.3\,\mu$G. The volume filling factor of the ropes is only poorly known from numerical simulations; the estimates range from 20% to perhaps about 100%. The magnetic fields produce a fluctuating Faraday rotation measure with $\langle \mathrm{RM} \rangle \simeq 10\,\mathrm{rad\,m^{-2}}$ on average in $r \leq 50$ kpc if they have large filling factor and are observed at a resolution of 0.1 kpc. Stronger Faraday rotation can be produced in the central regions.

Magnetic field generation in elliptical galaxies was discussed by Lesch & Bender (1990), but they considered a mean-field (α-effect) dynamo that needs overall rotation; this mechanism therefore cannot be effective in the X-ray halos of ellipticals. The fluctuation dynamo in elliptical (radio) galaxies was simulated by De Young (1980), but these simulations apparently had $R_\mathrm{m} < R_\mathrm{m,cr}$ as they resemble transient amplification of magnetic field by velocity shear rather than genuine dynamo action.

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