Magnetic Fields in Astrophysical Systems

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Magnetic Fields in Our Universe

Magnetic fields are pervasive in our Universe on all scales, see Fig. 1, from the earth and the solar system to galaxies and clusters of galaxies, with increasing evidence of their presence even in the voids of the cosmic web. They are known to be critical in many of the phenomena that are important in the formation of our Universe:

- **Star formation** – magnetic fields, via the magnetorotational instability, allow material to accrete on to the forming protostar by transporting angular momentum out from the accretion disc.
- **Jet production** – high velocity jets of material are common to many astrophysical systems and, although the exact mechanism of jet production is still uncertain, magnetic fields are thought to be critical to the accretion of material on to the central object and to the acceleration and collimation of the material that forms the jet.
- **Cosmic rays** – are high energy particles that are produced by supernovae and active galactic nuclei (AGN) and they require a magnetic field to accelerate them to the energy that we observe them at.

However, magnetic fields in astrophysical systems of galaxy size or greater are significantly less well understood. All spiral galaxies observed show the presence of a magnetic field that is coherent and ordered on the scale of the galaxy itself. The energy density of this field is similar in magnitude to the turbulent energy of the gas and the thermal energy of the galaxy and should play an important role in the formation and evolution of the galaxy. On the scale of clusters of galaxies magnetic fields are present in the gas between the galaxies, the intra cluster medium (ICM), but even the very origin of this field is uncertain. Our research is directed towards understanding the very large-scale magnetic fields in galaxies and clusters of galaxies by answering:

- What are the impacts of a magnetic field on the evolution of a spiral galaxy?
- What is the magnetogenesis mechanism for the very largest structures in our Universe?

Magnetic Fields in Spiral Galaxies

Magnetic fields are thought to originate in spiral galaxies from small initial seeds produced by supernovae and these are then amplified by the turbulence motions of the galaxy. The large-scale rotation of the galaxy then orders the magnetic field into the global field that is observed. Although the production of galactic magnetic fields is an intensely studied area, there has been significantly less work on the impact of the magnetic field on the evolution of the galaxy.

Recent work has shown that the arms in spiral galaxies are a transient feature, that form from local instabilities in the disc of the galaxy and dissipate on time scales of roughly 100Myrs. However this work does not include a galactic magnetic field and the magnetic pressure and magnetic tension force may effect the timescales on which the arms form and the time it takes them to dissipate. To investigate the impact of a galactic magnetic field on the formation of spiral arms in a galaxy we simulate the evolution of a spiral galaxy over a billion years with a magnetic field present.

The results of this simulation can be seen in Fig. 2. Regardless of the initial set up of the magnetic field the global rotation of the galaxy orients the magnetic field into the plane of disc. The magnetic field is maintained at a few microgauss, in agreement with the observed strength of galactic magnetic fields, and the rotation produces many reversals in the field structure. In agreement with previous work the stars and gas in the simulation form many spiral arm features during the simulation. The introduction of a magnetic field to the simulation causes the arm features to exist for a greater period of time and to wind up for a longer period of time before they dissipate.

Large-scale Magnetogenesis

For the very largest structures in our Universe the theories of magnetogenesis fall into two categories:

I. Primordial generation – seed magnetic fields are generated in the early Universe via inflation or at phase transitions, e.g. the quark to hadron transition.
   - Naturally produces observed coherence lengths
   - Naturally produces magnetic fields in voids
   - Seeds possibly too weak to be amplified to the magnitude observed in large-scale structures

II. Baryonic generation – large-scale structure is seeded by the magnetic fields ejected by galactic winds and AGNs.
   - Easily produces the observed field strength
   - Cannot explain observed coherence length
   - Extremely difficult to reconcile with observations of magnetic fields in voids

We simulated the formation of a galaxy cluster with a 10^{-14} G primordial field to investigate the amplification of the seed field and if it is capable of reproducing the observations of magnetic fields in galaxy clusters.

The galaxy cluster forms via the merger of many smaller objects and the final object is shown in Fig. 3. This merging of many smaller objects provides the energy to amplify the initial seed magnetic field to 2.3μG in the final cluster. The simulated cluster has a magnetic field strength in good agreement with that of observed galaxy clusters.

From the simulated cluster predicted observables can then be calculated:

- The X-ray and radio flux of the simulated cluster can be calculated. The strength and morphology of the “synthetic” emission agrees well with the observed radio and X-ray emission of galaxy clusters.
- A rotational measure (RM) indicates the line of sight magnetic field. A RM map of the simulated cluster was calculated and shows that the magnetic field is a patchwork coherent of the scale of a few kiloparsecs. This is good agreement with the RM maps of observed galaxy clusters.
- A primordial seed field is capable of reproducing the observations of large-scale magnetic fields in galaxy clusters and we hope to extend this work beyond the cluster scale.