INTENSE MAGNETIC FIELDS IN ASTROPHYSICS

V. CANUTO* and H. Y. CHIU**
Institute for Space Studies, Goddard Space Flight Center, NASA, New York, N.Y., U.S.A.

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Abstract. In this paper we summarize the current knowledge of research on the influence of intense magnetic fields on physical processes. The contents are summarized in the enclosed Table of Contents.

Table of Contents:

1. Introduction
2. The Source of Magnetic Fields in Astronomical Objects
3. Classical and Quantizing Fields
4. The Impossibility of Spontaneous Pair Creation in a Magnetic Field
5. Thermodynamic Properties
6. Radiation Processes in a Magnetic Field
7. Neutrino Processes in Magnetic Fields
8. Neutron Beta Decay
9. Dielectric Tensor for a Quantum Plasma
10. Transport Processes – Electron Conduction
12. Coulomb Bremsstrahlung in a Magnetized Plasma
13. Astrophysical Applications
Appendix I
Appendix II
List of Symbols
References

1. Introduction

The presence of magnetic fields in nature is a common phenomenon. Our earth possesses an approximate dipole field aligned at about 15° from its rotational axis with a strength of 0.5 G, and, according to fossil evidence, the field has an ancient history. The Sun, which is an average star, possesses a magnetic field of apparently complicated structure and configuration. The average value of the solar field (on the surface of the Sun) is 1 G, but this average is derived from a very heterogeneous distribution of fields ranging from zero to several thousands of gauss in sunspots. Many stars are also known to possess magnetic fields with strengths in excess of 500 G, which is the present lower limit of detectability of stellar magnetic fields (C67). In one case the average field strength is in excess of $3.4 \times 10^4$ G, about twice the saturation field of iron! Our Galaxy also possesses a magnetic field whose strength is a few times $10^{-6}$ G.

* NAS-NRC Senior Postdoctoral Resident Research Associate.
** Also with Physics Dept. and Earth and Space Sciences Dept., State University of New York at Stony Brook.
† These numbers refer to the References at the end of this paper.
The energy density of the field is comparable to the kinetic energy density of gas in our Galaxy, and the galactic field is believed to have a nonnegligible effect on the structure of our Galaxy (W64a, S66).

The role played by magnetic fields in astrophysics has been extensively discussed (S66, C67, W64, Ca67, CC68d, CC68e). Most fields discussed have strengths much less than $10^5$ G and such fields will hereafter be referred to as classical fields since for such fields the quantum effect is not likely to play any significant role in astrophysics. Exceptions are: (1) low temperature physics with a cryogenic temperature; (2) Zeeman splitting of atomic lines, which has been discussed elsewhere. Although on occasion fields more intense than $10^5$ G can still be regarded as classical, in no case can quantum effects be entirely neglected when the field strength is greater than $10^8$ G.

In the following sections we will briefly summarize the properties of classical magnetic fields, in particular, the source of magnetic fields in astronomical objects and the flux conservation law. In the remaining part of this paper, we will be concerned with the quantum effects of magnetic fields in astrophysics.

2. The Source of Magnetic Fields in Astronomical Objects

As far as we know, magnetic fields can only be generated and maintained by one of the following processes:

1. Moving charges (electric current).
2. Alignment of spin magnetic moment.
3. Alignment of magnetic moment due to orbital angular momentum of some types of atoms.
4. Landau Orbital Magnetized State.

The presence of an electric current in a conductor can generate a magnetic field according to the Maxwell equation:

$$\text{curl } H = \frac{4\pi}{c} j.$$  \hspace{1cm} (2.1)

However, the current density is subject to Ohmic dissipation. In conductors of ordinary size (e.g., coils in a small transformer) the Ohmic dissipation will dissipate a current completely in a matter of milliseconds. In the case of astronomical objects such as stars and nebulae, the conductivity is so high and the inductance so large that the time of decay ranges from millions to billions of years.

On the other hand, in order to align the spin or orbital magnetic moment, invariably a solid crystalline structure is needed. Further, the temperature cannot exceed the Curie temperature, which is of the order of $10^3$ K. As a result, although (2) and (3) are important processes in solid matter possessing permanent or semipermanent magnetism, they are of negligible importance in astronomical objects. The new process (4) which can give rise to a semipermanent magnetic field in dense bodies such as neutron stars and white dwarfs, will be discussed in a separate section.