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Review

Tracing magnetic fields with ground state alignment

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ABSTRACT

Observational studies of magnetic fields are vital as magnetic fields play a crucial role in various astrophysical processes, including star formation, accretion of matter, transport processes (e.g. transport of heat), and cosmic rays. The existing ways of magnetic field studies have their limitations. Therefore, it is important to explore new effects that can bring information about magnetic field. We identified a process "ground state alignment" as a new way to determine the magnetic field direction in diffuse medium. The consequence of the process is the polarization of spectral lines resulting from scattering and absorption from aligned atomic/ionic species with fine or hyperfine structure. The alignment is due to anisotropic radiation impinging on the atom/ion, while the magnetic field induces precession and realign the atom/ion and therefore the polarization of the emitted or absorbed radiation reflects the direction of the magnetic field. The atoms get aligned at their low levels and, as the life-time of the atoms/ions we deal with is long, the alignment induced by anisotropic radiation is susceptible to extremely weak magnetic fields ($1\,\mathrm{G} \gtrsim B \gtrsim 10^{-15}\,\mathrm{G}$). Compared to the upper level Hanle effect, atomic realignment is most suitable for the studies of magnetic field in the diffuse medium, where magnetic field is relatively weak. The corresponding physics of alignment is based on solid foundations of quantum electrodynamics and in a different physical regime the alignment has become a part of solar spectroscopy. In fact, the effects of atomic/ionic alignment, including the realignment in magnetic field, were studied in the laboratory decades ago, mostly in relation to the maser research. Recently, the atomic effect has been already detected in observations from circumstellar medium and this is a harbinger of future extensive magnetic field studies. It is very encouraging that a variety of atoms with fine or hyperfine splitting of the ground or metastable states exhibit the alignment and the resulting polarization degree in some cases exceeds 20%. A unique feature of the atomic realignment is that they can reveal the 3D orientation of magnetic field. In this paper, we shall review the basic physical processes involved in atomic realignment. We shall also discuss its applications to interplanetary, circumstellar and interstellar magnetic fields. In addition, our research reveals that the polarization of the radiation arising from the transitions between fine and hyperfine states of the ground level can provide a unique diagnostics of magnetic fields, including those in the early universe.

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Contents

1. Introduction

Astrophysical magnetic fields are ubiquitous and extremely important, especially in diffuse media, where there energy is comparable or exceed the energy of thermal gas. For instance, in diffuse interstellar medium (ISM), magnetic field pressure may exceed the thermal pressure by a factor of 10. In contrast, only a few techniques are available for the studies of magnetic field in diffuse medium and each of them has its own limitation. The Zeeman splitting can sample only relatively strong magnetic fields in dense and cold clouds (see [1]). In most cases, only line of sight component of the field can be obtained. In some cases, the disentangling of the magnetic field and density fluctuations is nontrivial. For instance, the Faraday rotation is sensitive to the product of the electron density and the line-of-sight magnetic field (see [2]). Finally, all techniques have their area of applicability, e.g. polarization of the synchrotron emission traces the plane-of-sky magnetic fields of the galactic halo (see [3]). New promising statistical techniques can measure the *average* direction of magnetic field using spectral lines fluctuations [4–6] or synchrotron intensity fluctuations [7].

The closest to the discussed technique of ground state alignment (henceforth GSA) are the techniques based on grain alignment and the Hanle effect. It is well known that the extinction and emission from aligned grains reveal magnetic field direction perpendicular to the line of sight (see [8] for a review). In spite of the progress in understanding of grain alignment (see [9] for a review), the natural variations in grain shapes and compositions introduce uncertainties in the expected degree of polarization. In contrast, Hanle measurements were proposed for studies of circumstellar magnetic fields and require much higher magnetic fields [10].

We should mention that all techniques suffer from the line-of-sight integration, which makes the tomography of magnetic fields difficult. As for the relative value, the most reliable is the Zeeman technique, but it is the technique that requires the strongest fields to study. In general, each technique is sensitive to magnetic fields in a particular environment and the synergetic use of the technique is most advantageous. Obviously, the addition of a new techniques is a very unique and valuable development.

Here, we discuss a new promising technique to study magnetic fields in diffuse medium. As we discuss below, the physical foundations of these technique can be traced back to the laboratory work on atomic alignment in the middle of the previous century ([11–15]; see Section 2.2 for details). Later papers [16,17] considered isolated individual cases of application of the aligned atoms mostly within toy models (see below for a brief review of the earlier development). Yan and Lazarian [18–21] provided detailed calculations of GSA for a number of atoms and through their study