# COSMIC MAGNETIC FIELDS

Magnetic fields are important in the Universe and their effects contain the key to many astrophysical phenomena that are otherwise impossible to understand. This book presents an up-to-date overview of this fast-growing topic and its interconnections to plasma processes, astroparticle physics, high energy astrophysics, and cosmic evolution. The phenomenology and impact of magnetic fields are described in diverse astrophysical contexts within the Universe, from galaxies to galaxy clusters, the filaments and voids of the intergalactic medium, and out to the largest redshifts. The presentation of mathematical formulae is accessible and is designed to add insight into the broad range of topics discussed. Written for graduate students and researchers in physics, astrophysics, and related disciplines, this volume will inspire readers to devise new ways of thinking about magnetic fields in space on galaxy scales and beyond.

PHILIPP P. KRONBERG is Research Professor Emeritus at the University of Toronto, Canada and Visiting Scholar at Los Alamos National Laboratory. He has served on or chaired advisory and management boards of many organisations and facilities and has received numerous awards and distinctions including a Humboldt Award, a Guggenheim Fellowship, and a Killiam Fellowship. For over thirty years Kronberg has pioneered both measurements and physical and mathematical analyses to deduce astrophysical magnetic fields on many scales, from our Milky Way to the most distant quasars.

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This book is dedicated to my parents Philipp Kronberg and Jean Davidson Kronberg for their unwavering support of my career in astrophysics and radio astronomy
and
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# Contents

# Preface

Recent observational advances reveal the widespread existence of magnetic fields in the Universe, and produce much firmer estimates of magnetic field *strengths* in both interstellar space and some regions of intergalactic space. Microgauss-level fields are a common component of spiral galaxy disks and halos. Current measurements can detect magnetic fields, directly or indirectly, in the late universe of galaxies as far as "observational reach" can take us. This is at least to $z \sim 3$, and means that they have not globally changed into the past, that covers at least 90% of the lookback time to the origin of the Universe.

They appear to pervade the intracluster medium of clusters of galaxies, and indeed well beyond the cluster core regions. Strengths of ordered magnetic fields in the intracluster medium of cool core galaxy clusters exceed what is typical for the interstellar medium of the Milky Way. This challenges us to explain how they were first generated, and then regenerated to the unexpectedly high measured levels, and to answer the related question of how such widespread magnetic fields influenced the formation of stars and galaxies.

In this book I describe how extragalactic magnetic fields on different scales and in different astrophysical systems can be probed and measured. I also discuss some new methods which could be used to indirectly infer field strengths that are otherwise beyond the reach of direct measurement.

Some basic physical processes responsible for the regeneration of fields are outlined, including mechanisms of magnetic diffusivity and dissipation that influence field amplification. Fast dynamo processes associated with galaxy halo outflow and radio jets can demonstrably magnetise large volumes of intergalactic space; nonetheless, the mechanisms are far from completely understood. Fast-acting dynamo mechanisms appear to operate in galaxies through galaxy outflow, in extragalactic jets and lobes, and possibly in cooling flow clusters. Magnetic reconnection and related magnetohydrodynamic (MHD) processes may also be important.

Whether the intergalactic fields we now observe were originally produced in stars and galaxies, or in the pre-Recombination early Universe is a question with many ramifications, and increasingly discussed. It seems clear that stars and galaxies can seed and regenerate magnetic fields in various ways, post-Recombination. But magnetic fields may have also emerged earlier during Inflation, and perhaps integral to creation of the first subatomic particles as they emerged from the primordial "soup" in the course of enormous energy transfers.

Additional or colour-enhanced illustrations can also be found at the URL www.cambridge.org/9780521631631.

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