Kinetic axi-symmetric gravitational equilibria in collisionless accretion disc plasmas

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(Dated: November 2, 2018)

A theoretical treatment is presented of kinetic equilibria in accretion discs around compact objects, for cases where the plasma can be considered as collisionless. The plasma is assumed to be axi-symmetric and to be acted on by gravitational and electromagnetic fields; in this paper, the particular case is considered where the magnetic field admits a family of toroidal magnetic surfaces, which are locally mutually-nested and closed. It is pointed out that there exist asymptotic kinetic equilibria represented by generalized bi-Maxwellian distribution functions and characterized by primarily toroidal differential rotation and temperature anisotropy. It is conjectured that kinetic equilibria of this type can exist which are able to sustain both toroidal and poloidal electric current densities, the latter being produced via finite Larmor-radius effects associated with the temperature anisotropy. This leads to the possibility of existence of a new kinetic effect - referred to here as a "kinetic dynamo effect" - resulting in the self-generation of toroidal magnetic field even by a stationary plasma, without any net radial accretion flow being required. The conditions for these equilibria to occur, their basic theoretical features and their physical properties are all discussed in detail.

PACS numbers: 95.30.Qd, 52.30.Cv, 52.25.Xz, 52.55.Dy, 52.25.Dg

I. INTRODUCTION

This paper is concerned with dynamical processes in astrophysical accretion disc (AD) plasmas and their relationship with the accretion process. The aim of the research programme of which the first part is reported in the present paper is to provide a consistent theoretical formulation of kinetic theory for AD plasmas, which can then be used for investigating their equilibrium properties and dynamical evolution. Note that what is meant here by the term "equilibrium" is in general a stationary-flow solution, which can also include a radial accretion velocity. Apart from the intrinsic interest of this study for the equilibrium properties of accretion discs, the conclusions reached may have important consequences for other applications and for stability analyses of the discs. In this paper we consider the particular case where the AD plasma contains domains of locally-closed magnetic surfaces where there is in fact no local net accretion. We then focus on these domains. We do this, both because this represents a situation which is of considerable potential interest, but also because it leads to some significant simplifications of the discussion. In subsequent papers, we will proceed to consider more general cases.

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A. Astrophysical background

Accretion discs are observed in a wide range of astrophysical contexts, from the small-scale regions around proto-stars or stars in binary systems to the much larger scales associated with the cores of galaxies and Active Galactic Nuclei (AGN). Observations tell us that these systems contain matter accreting onto a central object, losing angular momentum and releasing gravitational binding energy. This can give rise to an extremely powerful source of energy generation, causing the matter to be in the plasma state and allowing the discs to be detected through their radiation emission [1–3]. A particularly interesting class of accretion discs consists of those occurring around black holes in binary systems, which give rise to compact X-ray sources. For these, one has both a strong gravitational field and also presence of significant magnetic fields which are mainly self-generated by the plasma current densities. Despite the information available about these systems, mainly provided by observations collected over the past forty years and concerning their macroscopic physical and geometrical properties (structure, emission spectrum, etc.), no complete theoretical description of the physical processes involved in the generation and evolution of the magnetic fields is yet available. While it is widely thought that the magneto-rotational instability (MRI) [3] plays a leading role in generating an effective viscosity in these discs, more remains to be done in order to obtain a full understanding of the dynamics of disc plasmas and the relation of this with the accretion process. This requires identifying the microphysical phenomena involved in the generation