The Drift-Alfvén Model for a Magnetized Plasma Applied to Saturn's Polar Vortices

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The paper details the fundamental assumptions necessary for the derivation of special relativity theory, in particular for the derivation of Lorentz coordinate transformation. It shows that the usual postulate of the light speed constancy is unnecessary. This generalization is useful for studying the space-times with gravitational fields present, including the space-time of the Universe, since it is well known that the gravitational potential affects not only clock rates, but also the speed of light.

The hexagon above Saturn's north pole, and its long lived state of equilibrium, may result from a pinched plasma column aligned with Saturn's magnetic axis coupled to the conductive upper atmosphere. Cassini data analyzed by Gurnett et al. describes field aligned currents as a possible mechanism for coupling between magnetospheric plasma and the conductive layer of Saturn's upper atmosphere. The hexagon and its stability can be explained by the drift-Alfvén model for a magnetized plasma due to the near perfect alignment of Saturn's magnetic and rotational axes. The alignment of the magnetic and rotational axes results in a smooth transfer of angular momentum from magnetized plasma in Saturn's ionosphere to the denser conducting fluid layer of the upper atmosphere's polar circulation.

1. Introduction

A hexagonal vortex above Saturn's North pole was discovered in 1988 after stitching together images taken during the Voyager 1 & 2 encounters of the ringed giant. The flybys occurred in November 1980 and August 1981. Nearly thirty years after swooping past Saturn, as the Voyager spacecraft are now on the verge of leaving the solar system, the Cassini mission, currently exploring Saturn and its complex of moons and rings, confirmed the surprising persistence of the hexagon in 2009. At that time, astrophysicists had yet to determine the cause, the energy throughput, nor an explanation for the longevity of the spectacular polygon penetrating 75 km deep into the Cronian atmosphere [1, 2].

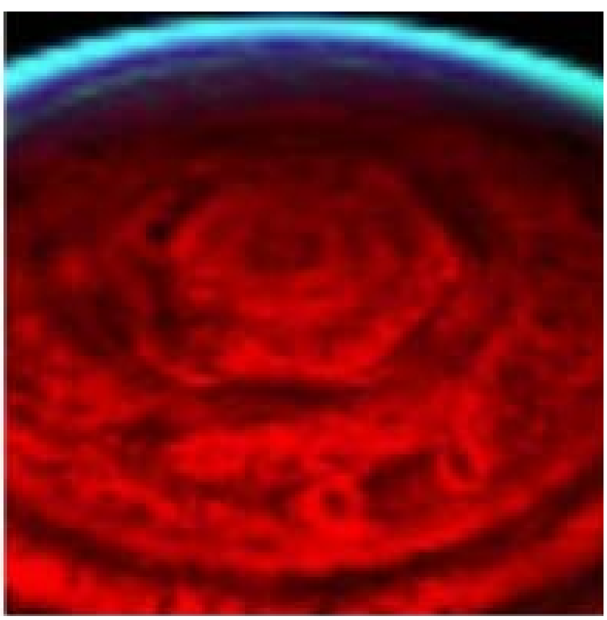

Fig. 1. Saturn's persistent hexagon. Image credit: NASA/JPL/ University of Arizona

2. Background

Research on stable polygonal structures in fluids includes an initial interpretation in 1990 as a stationary Rossby wave [3], analysis of convective upwelling, and experiments by Vatistas in 1990 which were the first to demonstrate Kelvin's equilibrium states [4]. Another experiment in 2005 utilized a rotating disc at the bottom of a cylinder of liquid [5], as did Vatista's 1990 experiment. A new experiment and accompanying analysis in 2007 by Aguiar et al. proposes that "Saturn's long-lived polygonal structures correspond to wavemodes caused by the nonlinear equilibration of barotropically unstable zonal jets." The experiment consisted of a liquid in a cylindrical rotating tank, with a base and lid each divided into two concentric rings of equal width. The inner and outer rings of the base and lid rotating at different speeds produced polygonal stationary shear walls along their interface, including a N=6 hexagonal shape. An accompanying paper of the experiment comparing an analysis of spacecraft observations was accepted for publication in October, 2009 [6].

Analogous to rotating liquids, plasma vortices have been shown for over a century to demonstrate remarkably similar properties. Laboratory experiments conducted with a Malmberg-Penning trap demonstrate that an electron vortex is equivalent to a fluid vortex. The formation of stable 2-D patterns in a Malmberg–Penning trap was first reported by Fine et al. in 1995 [8].

The motion of electrons will form a pinched column around the axis of a strong magnetic field and behave much like an ideal 2-dimensional fluid. The flow of electrons interacting with their own self-generated electric field, evolves into a system of columns described by the 2-D Drift-Poisson equations.

The parameters specific to an electron column are the magnetic field, particle velocity, electrostatic potential and particle density. Apart from their specific parameters, these equations are identical to the 2-D Euler equations describing an ideal 2-D fluid. Under certain experimental conditions, the two systems are indistinguishable [9].

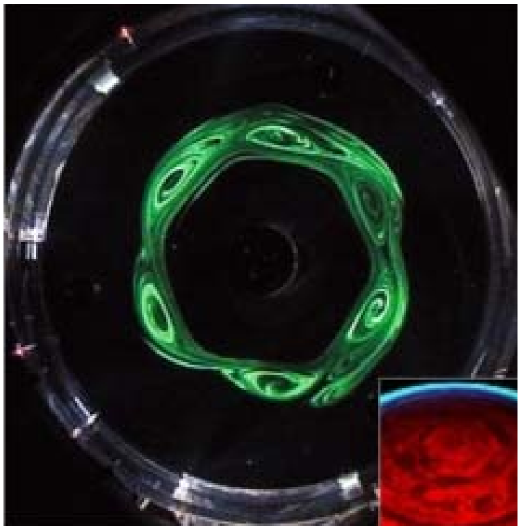

Fig. 2a. Top view of hexagon created in the Aguiar et al. experiment compared to Saturn's hexagon. Credit: Anna Barbosa Aguiar; (inset) NASA/JPL/University of Arizona

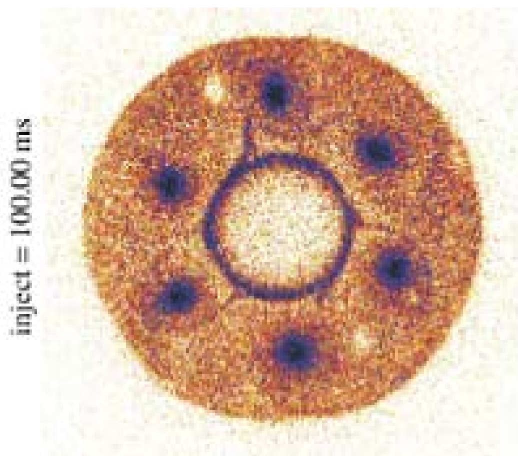

Fig. 2b. Image of N=6 electron column on phosphorous witness plate in Malmberg-Penning trap, 100.00 ms after electron injection. Image credit: Durkin 1998

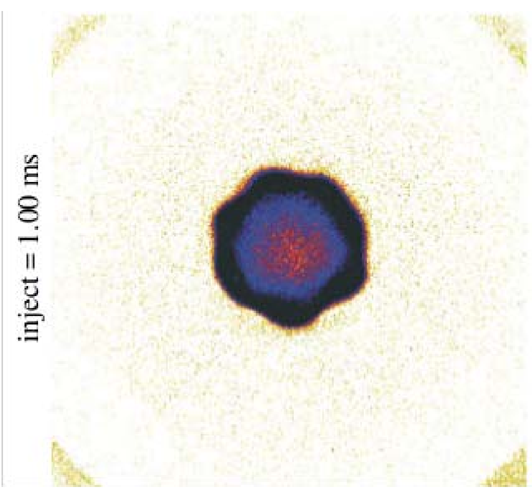

Fig. 2c. Image of N=7 electron column on phosphorous witness plate in Malmberg-Penning trap, 1.00 ms after electron injection. Image credit: Durkin 1998

The diocotron instability, first examined theoretically in 1950 and observed in early experiments in 1956, is perhaps the most ubiquitous instability in a low-density non-neutral electron plasma column confined radially by a uniform axial magnetic field. The diocotron instability is driven by a sufficiently strong shear in the angular rotation velocity of the plasma column. Whenever the density profile has an inverted population as a function of the radial coordinate (an off-axis density maximum), the sign of changes over the radial extent of the plasma column and the shear in the angular flow velocity can provide the free energy to drive the Kelvin–Helmholtz-like instability known as the diocotron instability [8]. This regime of instabilities includes both transitional states and states of equilibrium.

Stable states of equilibrium can exist indefinitely with lobes of 6 or fewer, with the six lobed hexagon being the highest order of stability, while 7 or more lobes are merely quasi-stable [9].

A contemporary paper by Vatistas et al., who conducted the initial 1990 fluid experiments, analyzes the comparison between recent fluid and plasma based experiments. "The comparison shows similar patterns of vortices produced in two completely different systems, providing the first experimental evidence of the direct analogy between the polygonal satellite vortices observed in a normal fluid and the vortices in pure electron plasma." [10]

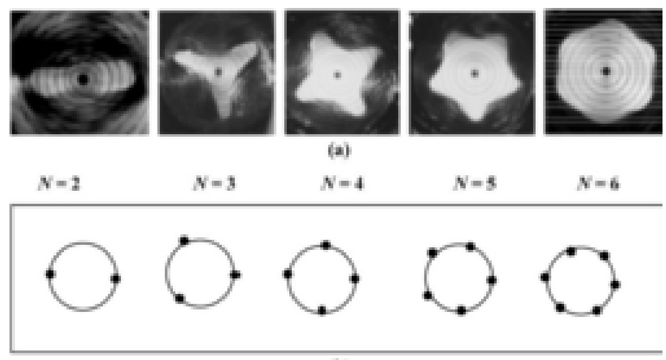

Fig. 3. (a) Typical equilibrium patterns in the hydrodynamically analogous experiment. (b) A schematic of the observed stable pure electron vortex configurations in a Malmberg–Penning trap by Durkin [12] Image credit: Vatistas et al.

3. Analysis

At Saturn the radio emission that is used to determine the radio rotation rate occurs in the frequency range from about 50 to 500 kHz and is called Saturn Kilometric Radiation (SKR). The rotation rate most commonly quoted is obtained by analyzing the periodic rotational modulation of radio emissions.

These radio emissions are generated by charged particles whose motions are controlled by the planetary magnetic field [14]. Although the clouds that form the hexagon have a velocity in excess of 100 m/sec, the pattern actually rotates in sync with the radio rotation period. Observed kilometric radio emissions and the hexagon are likely to be connected to a common cause [13].

References

[1] A. Einstein, *Annalen der Physik* **17**: 891 (1905).

[2] J. Rotman, **An Introduction to the Theory of Groups**, Springer-Verlag (1994).