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Transport in Magnetized Correlated Plasmas

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14. ABSTRACT
Experiments and theory will characterize the confinement properties of plasmas in magnetic fields, in the temperature regime where inter-particle correlations are significant. The experiments will be performed on two existing apparatuses: the "IV" apparatus contains Mg+
ion plasmas with sophisticated laser diagnostics and control techniques; and the "CamV" apparatus contains pure electron plasmas or e-/H- plasmas with detailed camera diagnostics. Theory will characterize the plasma dynamics with emphasis on quantitative comparison to
experiments. Specifically, this research will characterize the "long-range" collisions causing particle diffusion and heat diffusion across the magnetic field, in the regimes from weak to moderate inter-particle correlation. Prior experiments and theory for un-correlated plasmas has characterized the important dynamical effects of electric fields, plasma flow shear and finitesize (boundary) effects. One surprising dynamical effect is "collisional caging", where noise fluctuations cause particles to collide multiple times. Another surprising dynamical effect is
that the ubiquitous "diocotron" mode can cause enhanced centrifugal separation of disparate mass species. This research will extend these dynamical perspectives into the lower temperature regime of strong inter-particle collisionality. These experiments will be performed
on research devices optimized for simplicity, controllability, and quantitative diagnostics. However, the understandings developed have applicability to diverse magnetized plasma technologies, ranging from anti-matter traps to microwave oven magnetrons to plasma
thrusters for satellite propulsion.

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John Luginsland, Plasma and Electro-Energetic Physics

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ACCOMPLISHMENTS
Significant experimental and theoretical progress was made in each of the 5 proposed Objectives, and potentially disruptive advances were made regarding electric fields in solar and heliospheric plasmas.

Objectives:
1) "Experiments will extend measurements of cross-field particle diffusion from the low-collision regime into the correlated regime of $\Gamma \geq 1$, characterizing the dynamical effects of rotational shear and finite-size/ boundary effects."

--Dr. Anderegg developed led an experimental campaign with grad student Jacob Saret exploring diffusive effects in accessible regimes on the IV apparatus, and discussed results at APS/DPP2019 "Test Particle Diffusion in Correlated Plasmas". The "boundary effects" determined by an imposes magnetic "separatrix" were measured experimentally, and published in Phys.Rev.Letters (2019) as "Plasma Heating Due to Cyclic Diffusion Across a Separatrix.

--Prof. Dubin gave an invited talk at Vlasovia-2019 discussing a new theory development on "Parametric Instability Driven by Weakly Trapped Particles in Nonlinear Plasma Waves"; here, the novel boundary effects are formed by soliton-like waves. This was expanded upon at DPP-21 in a talk entitled "Recent advances in understanding neoclassical transport processes in nonneutral plasmas.

2) "Experiments will test Dubin's recent theory predicting enhanced collisional slowing of particles due to noise-induced "collisional caging" in long-range collisions."

--Dr. Anderegg led graduate students Patrick Steinbrunner and Jacob Saret in an experimental campaign which was reported at DPP-20 and DPP-21, "Direct Measurement of Enhanced Particle Slowing from 1D Long-Range Collisions". These results are being prepared for publication.

3) "Experiments will extend measurements of cross-field heat conductivity from the low-collisional regime into the correlated regime."

--Dr. Kabantsev supervised graduate student Kurt Thompson in experiments on CamV, leading to his Ph.D. thesis titled "Experiments on Cross-Magnetic_Field Heat Transport in Magnetized Pure Electron Plasmas (2020). The enhanced heat transport is up to 10^5 times larger than the prediction from "classical" plasma collisions.

4) "Experiments will measure the enhanced centrifugal transport of H- in electron plasmas".
--Dr. Kabantsev led (Italian) graduate student Nicola Panzeri in a series of

experiments on CamV with trapped H- ions, reported at DPP-19 as "e-/H- Plasmas: Exceptional inwards transport from a Rotating Wall drive, with rapid outwards convection afterwards". Exploration of H- effects is continuing.

5) "As they develop, new theory perspectives on collisional transport in the 2D and 3D regimes will be related to other fields of physics, from fluid dynamics to space plasmas; and to practical devices, from cryogenic anti-matter containment to energetic Hall thrusters."

-- Prof. Driscoll has performed data analysis on 20 years of ACE satellite magnetic measurements at 1.AU, supplemented by radial dependencies from Ulysses and Mariner at 0.3 - 5.AU. The analysis includes the effects of charged particles and electric fields, expanding the traditional "uncharged fluid" perspective of Magneto Hydro Dynamics, and distinguishes heliospheric dynamical effects from the pervasive effects of entropic noise.

-- The satellite measurements led to development of a model of "electric jets" formed in the solar photosphere, providing an energy basis for the Solar Wind and the "heating" of the solar corona. These results have been presented at APS/DPP-19 and -20, as well as AGU/FM-19 and -20, and are being prepared for publication. NNP.ucsd.edu/Solar/

IMPACTS

The theory and experiments on single-charge-sign plasmas at low temperatures (with moderate correlation) directly impacts the many experimental campaigns to contain and diagnose anti-matter, and development of techniques of ion-trapping for quantum computing. Profs. Dubin and O'Neil continue to collaborate closely with several of these groups.

Broadening the solar-science perspective beyond MHD to include particle and electric effects could have beneficial effects on our understanding of the Sun and heliosphere.

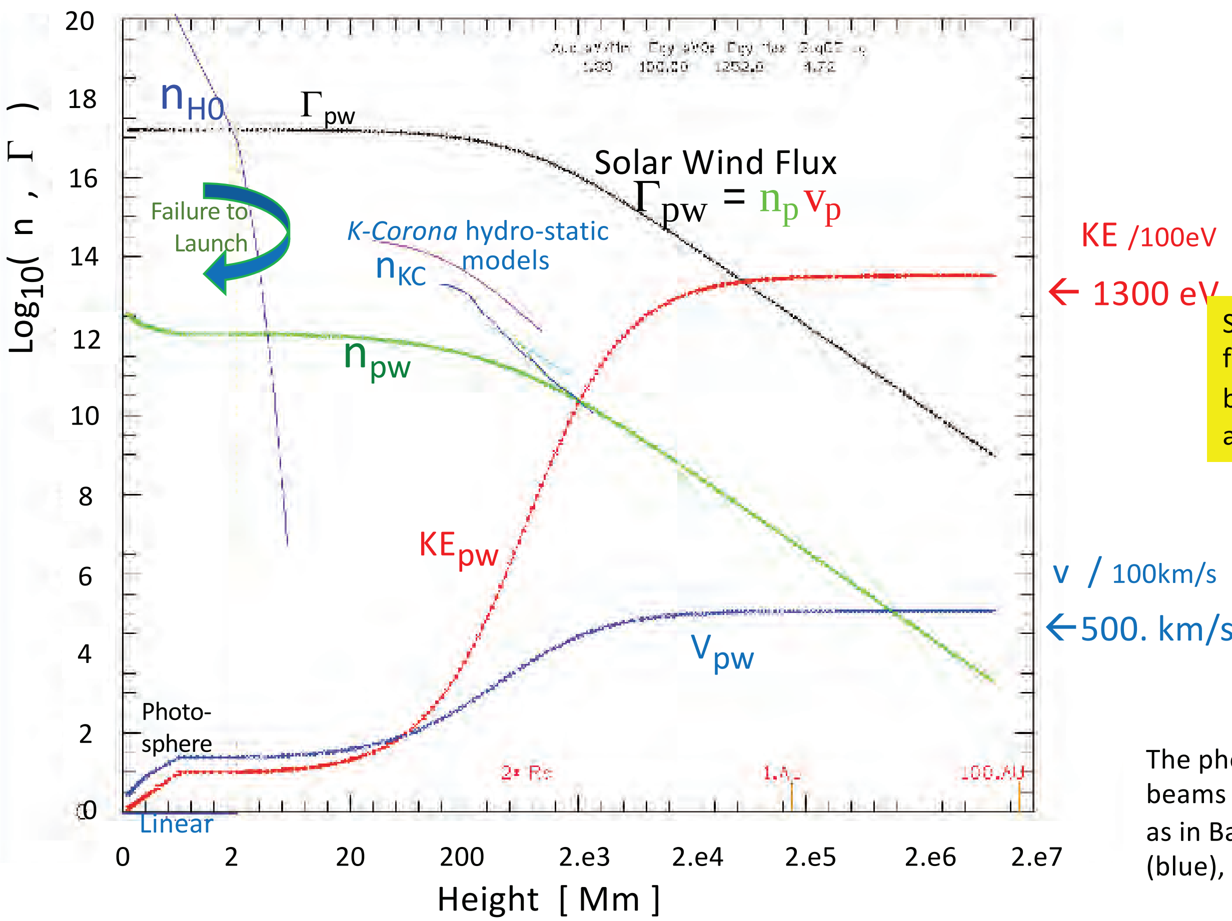
CHANGES
Dr. Anderegg retired from UCSD in July-21, enabling greater support for Dr. Kabantsev.

TECHNICAL UPDATES
From AGU/FM-20

Photon-Driven Solar Wind p+ Flux, Density, Velocity, Energy assuming average $\sigma_{\gamma e} = 3.4\text{x}10^{-24}\,\text{m}^2$

$$\frac{d}{dr}\mathcal{E}_p = -m_p\Psi' + eE(r)$$
$$-\nu_c(p^+, H^0)$$
$$\mathcal{E}_{p+}(\rho) \sim \mathcal{E}_0 + (1.3\text{keV})[1 - 1/\rho]$$

$$\text{v}_p(\rho) \sim (500.\text{km/s})[1 - 1/\rho]$$
$$n_p(\rho) \sim 3\text{x}10^{11}\ \rho^{-2}\ \text{m}^{-3}$$
$$\Gamma_p(\rho) \sim 1.6\text{x}10^{17}\ \rho^{-2}\ \text{s}^{-1}\text{m}^{-2}$$
$$\rho \equiv r / R_s$$



Starting in the photosphere, thermo- and photo-electric fields accelerate a "runaway" beam of protons, neutralized by electrons. With the modelled $\sigma_{\gamma e}$, the proton energy asymptotes to 1.3keV within several solar radii.

A more detailed 3-dim model would include beam "pinching" and filamentation, well below the Mm scale of solar surface granulations.

The photon coupling $\sigma_{\gamma e}$ depends strongly on e-/p+ correlation and density, so some beams would return to the solar surface ("failure to launch").

The photon scattering from from the launched and returning beams appears as the K-Corona, without hydro-static heating, as in Badalyn 1985 (magenta), Strachan 1993 (cyan), Fisher 1995 (blue), and Cranmer 1999 (green).

Spectrum of Magnetic Fluctuations : ACE MAG @ 1.AU

16.sec data, 1998.0 -> 2019.4