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X-ray imaging spectroscopy in laboratory astrophysics studies of complex hydrodynamic phenomena

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Remarkable plasma hydrodynamic phenomena such as supersonic jets have been observed to emerge from a wide variety of astrophysical systems, however a number of questions on their formation mechanisms and morphology are still open. Laboratory experiments employing the plasma produced by high power lasers can be scaled to astrophysical systems by matching dimensionless scaling parameters, thus providing the only way to study astrophysical phenomena in controllable conditions in laboratory, and, in turn, to verify and improve their theoretical description.

Extended experimental program has been done recently implementing high energy ns laser pulses and external B-field generator to study the development and evolution of a stable large-aspect-ratio supersonic jets[1] or even more complex magnetized accretion columns[2] and turbulences caused by plasma instabilities[3]. The task imposes strong requirements on diagnostic approaches being capable to mitigate with complexity of far expanding, and sometimes interacting, high-speed plasma flows evolving in space and time.

The talk is focused on the development and implementation of the combined X-ray imaging spectroscopy method[4] that allow us to investigate the complex plasma hydrodynamics involved in such experiments and to determine together the emissivity, electron temperature and density profiles at every stage of plasma flow evolution. It considers both recombining stages with definitely non-stationary ionization state and re-ionization stages in shocked regions[5].

The implementation of the method particularly resulted in revealing the mechanisms of bipolar supersonic jets collimation by differently oriented magnetic field in young star formation[1], as well in better understanding in the development of plasma instabilities while the supersonic plasma ejecta propagates across magnetic field lines[3].

Then further, the formation of Herbig-Haro objects and accretion columns is studied while the jets interact with an ambient plasma media[6]. It is shown that plasma collimation due to shocks against a strong magnetic field can lead to stable, astrophysically relevant jets that are sustained over time scales 100 times the laser pulse duration, even in the case of strong variability at the source.

In the interaction of magnetically collimated plasma jet with a solid obstacle the accretion process was modeled, and the high-density region of the stellar chromospheres[2] was mimicking. In accretion columns the formation of a hot plasma shell enveloping the shocked core is discovered giving one of the possible explanations for systematic discrepancy between mass accretion rates derived from X-ray and optical astronomical observations[2].

We also infer magnetic field compression in the interpenetration of two collisionless, high-velocity (0.01–0.1c) quasi-neutral plasma flows[7]. This is evidenced through observed plasma stagnation at the flows collision point, which PIC simulations suggest to be the signature of magnetic field compression into a thin layer, followed by its dislocation into magnetic vortices.

The first complete description of the three-dimensional dynamics of a laser-driven plasma plume expanding in a 20-30 T transverse magnetic field was done as well[3]. It is found the collimation of the plasma into a slender, rapidly elongating slab, whose plasma-vacuum interface is unstable to the growth of the "classical," fluidlike magnetized Rayleigh-Taylor instability. As the magnetic field strength is increased, more plasma is confined close to the target and is heated by magnetic compression. The dense slab rapidly expands into vacuum, however contains only few percent of the total plasma. As a result of the higher density and increased heating of the confined plasma, there is a net enhancement of the total x-ray emissivity induced by the magnetization.

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