

SOL convective transport by blobs

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Background

A tokamak fusion plasma has three radial zones:

- the *core plasma*, encompassing most of the plasma volume, where the fusion reaction occurs. The magnetic field lines in this region form closed magnetic flux surfaces and do not touch material boundaries.
- the *edge plasma*, connecting the core to the outer region. The edge plasma has closed field lines, but unlike the core, is cooler and therefore highly collisional. This region is usually bounded by a magnetic separatrix.
- the *scrape-off-layer (SOL)*, a region of open field lines which exhausts the particles and energy from the main plasma to a separate region called the *divertor*, where the magnetic field lines terminate on material boundaries.

The transport of heat and particles across these three regions is a highly turbulent process. Experiments on many tokamaks have shown that the edge plasma provides a crucial, and as yet poorly understood, boundary condition for the core turbulence and transport, and thus the edge controls the global plasma confinement (and the fusion reactivity). The impact of turbulent transport on the SOL is also important for the issues of divertor heat exhaust, particle balance, and impurity control. SOL turbulence differs from core turbulence in several interesting ways: the open field lines introduce sheath boundary conditions which can modify the underlying instability drives and give rise to new phenomena. These new phenomena include turbulent waves with non-Gaussian statistics and the formation of coherent structures which propagate radially and poloidally in the SOL plasma.

In collaboration with scientists at LLNL and UCSD, Lodestar has an active research program in the general area of edge and SOL plasma stability, turbulence and transport.

Blob transport

Our most recent work in this area has focused on the theory of convective transport in the SOL by coherent structures known as "blobs".^{1,2} A variety of experimental diagnostics on many fusion devices confirm the existence of localized, radially propagating objects in the SOL plasma, which cause a broadening of the density

profile into the far SOL and an increase in recycling of neutrals from the main chamber walls. This effect is important because it "short circuits" the divertor and changes the physical boundary conditions for the core turbulence. The blob theory is an attempt to explain this behavior in a simple model.

Blobs are thought to arise near the separatrix as a result of edge turbulence, probably as a result of the change from closed to open field lines. Although turbulent in origin, they are observed to move as coherent (non-turbulent) objects. The term "blob" refers to its shape seen in the 2D plane; in 3D it is actually a filament, localized perpendicular to the magnetic field but extended a large distance along the B field lines. A blob contains concentrations of density, temperature, and vorticity higher than the surrounding plasma, because it convects the values of these quantities from its birth place near the separatrix outwards towards the colder and more tenuous SOL plasma.

The theory of blob convection stems from the simple observation that a density blob becomes charge polarized under the action of a species-dependent force. In the presence of a radial force that causes electrons and ions to drift in opposite (poloidal) directions, the blob charge distribution polarizes. A poloidal electric field is created and the resulting $\mathbf{E} \times \mathbf{B}$ drift moves the blob outwards radially across the SOL. Examples of such forces include the curvature or ∇B force^{1,2} in a toroidal device like the tokamak, the neutral wind force,³ and the centrifugal force¹ for a rapidly rotating linear plasma device. For the curvature force, it is simple to work out an analytic solution for a circular cross-section density blob with radius a propagating in the absence of a background density (or with an internal density much larger than the background) assuming a Gaussian density profile, $n(r) = n_0 \exp[-(r/a)^2]$. Balancing the sheath current flow term with the curvature term in the vorticity (charge balance) equation, one obtains the following solution for the radial velocity v_x in the electrostatic limit:

$$v_x = \frac{q}{2a}, \quad (1)$$

where $q = L_{||}/R$ is the curvature parameter. Here, we have used dimensionless units in which lengths are scaled to the gyroradius and frequencies to the cyclotron frequency, so that $v_x/c_s \rightarrow v_x$ and $a/\rho_s \rightarrow a$. The result in Eq. (1) implies that *smaller blobs travel faster than larger ones* (and penetrate farther into the SOL, when the parallel loss of density is included in the model).

Many qualitative features of the experiments, such as relatively flat density profiles and transport coefficients increasing toward the wall, emerge naturally from the

blob transport paradigm because of this simple result. It also follows that the SOL density and flux profiles due to an ensemble of blobs is a sensitive function of the blob size distribution. For example, taking a power law distribution of blob sizes, $f(a)=1/a^p$, and doing an ensemble average² over the contributions of different size blobs, we can compare the SOL profiles obtained for two different values of the exponent p . The results are shown in Fig. 1, taken from Ref. 2:

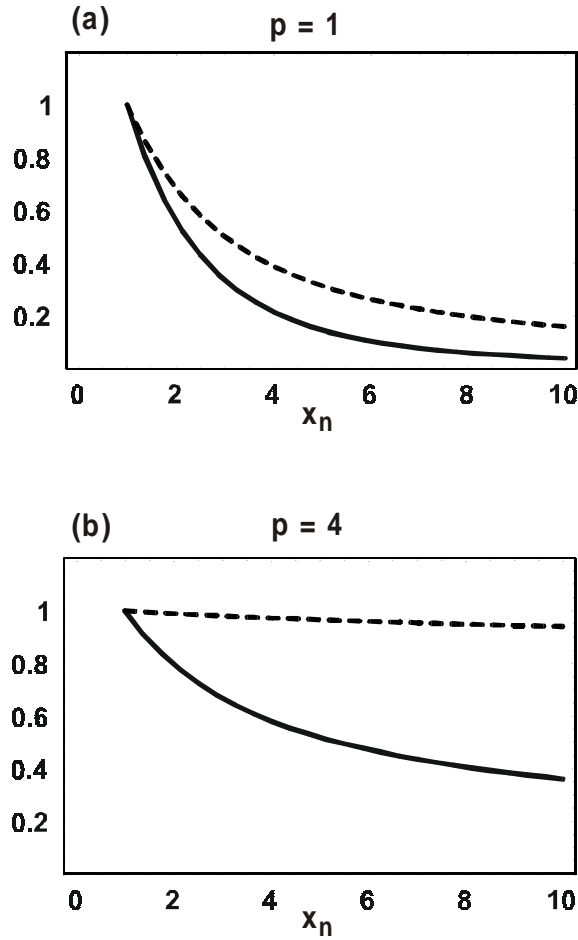


Fig. 1 Profiles of normalized density (solid line) and radial particle flux (dashed line) vs normalized radial coordinate x_n for (a) $p = 1$ and (b) $p = 4$

This plot corresponds to the parameters $B = 30$ kG, $T_e = 50$ eV, $R = 100$ cm, and $L_{||} = 4\pi R$. For $p = 1$ the large slow blobs dominate the transport. They do not penetrate very far before decaying due to parallel particle flow to the sheaths, yielding exponentially decaying profiles. For $p = 4$ the small fast blobs dominate the transport. Since the small

blobs move faster, they can travel much farther before decaying and therefore produce flatter density and flux profiles, consistent with the estimate given in Eq. (1) from the single blob model. The behavior in Fig. 1(b) is qualitatively similar to the “Main Chamber Recycling Regime” on the Alcator C-Mod tokamak, characterized by flattened density profiles and large recycling near the wall.

The analytic model just described can be generalized to include more physics and the resulting equations solved numerically. For example, electromagnetic corrections to the blob model were considered,⁴ and it was shown that blob transport is dramatically enhanced by electromagnetic effects at high density. This effect can lead to a density limit in a reduced-2D electromagnetic model. The relationship of this work to the experimentally observed density limit in tokamaks is still unclear.

Blob stability

Another line of enquiry was motivated by the dependence of the blob transport on the blob size distribution, illustrated in Fig. 1. This suggests that if the blobs are internally unstable and break apart, the blob transport will actually increase. We have therefore undertaken a study of instabilities driven by the blob's internal density, pressure, and potential profiles. Each of the forces that cause blob propagation in equilibrium can also drive an instability. The important question is whether the growth rate of the instability is fast enough to affect the blob's shape and velocity before it reaches the wall.

By analytic calculations and numerical 1D and 2D simulations we have shown that blobs can fragment due to curvature-driven sheath-interchange.⁵ These simulations also incorporated the effects of dissipation and of a background density on the blob dynamics. The background density affects the blob shape and velocity in ways that agree qualitatively with the experimental data.⁵ Result of a typical run are shown in Fig. 2.

In Fig. 2, we see that an initially circular blob deforms and bifurcates as the sheath-interchange instability reaches the nonlinear stage; the result is to create two elongated blobs with smaller poloidal extent than the original blob; since the charge polarization occurs over this distance to create a poloidal electric field, the new blobs $\mathbf{E} \times \mathbf{B}$ drift outwards faster than the original blob. When inertial effects are considered, Kelvin-Helmholtz instabilities are also seen in the simulations, at least for smaller blobs.⁶ Thus, the net transport due to an ensemble of blobs will depend on the effect of such instabilities.

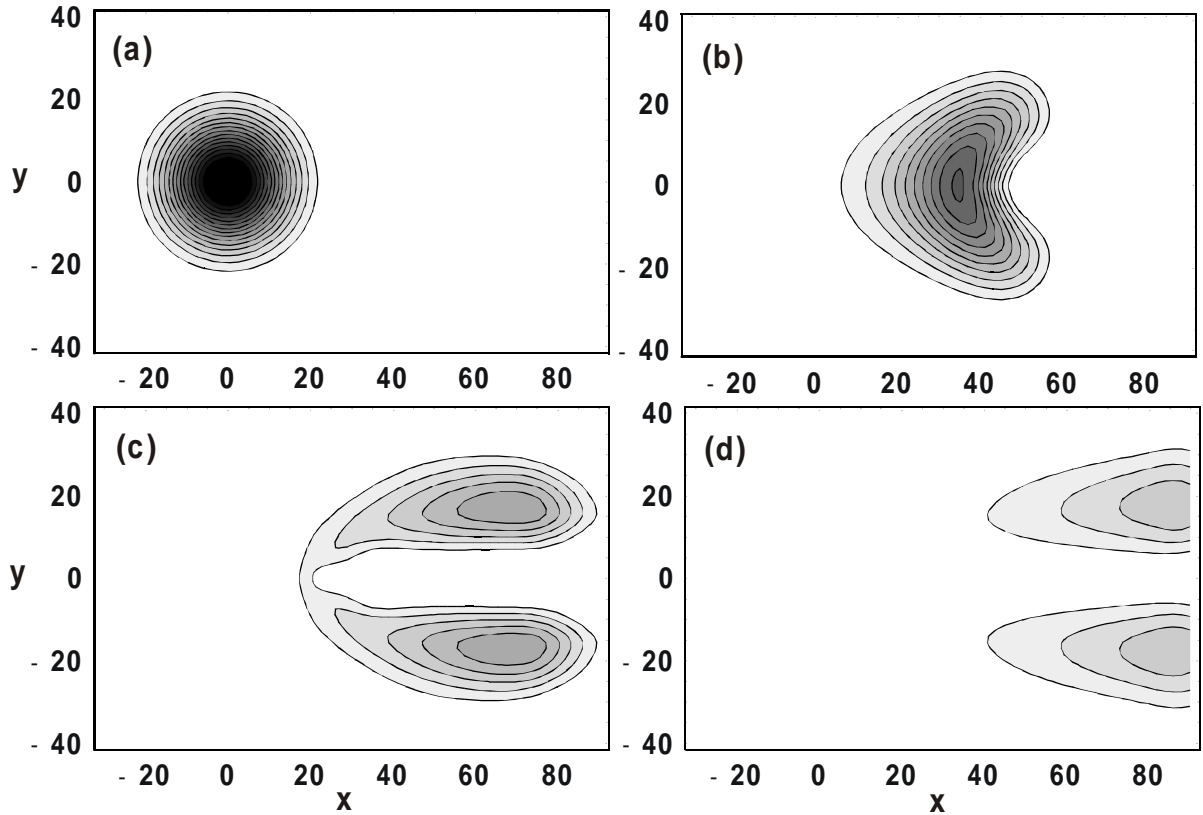


Fig. 2 Blob propagation with finite viscosity showing weak instability and subsequent bifurcation for the case of small background density (1% of the peak blob density). Results of the simulation are shown at four values of t/τ_C : (a) 0, (b) 6, (c) 9, and (d) 12, where τ_C is the time to convect one blob radius.

More recently, we have begun an analysis of the rotational stability of blobs.⁷ Recall that the open field lines in the SOL terminate in Bohm sheaths with electrostatic potential of order $3T_e$, where T_e is the local electron temperature at the sheath entrance. If we consider the case of a "hot" blob that is not in thermal equilibrium with the background plasma, it will have an internal temperature profile $T_e(r)$ that is monotonically decreasing in r (the internal blob radial coordinate); the corresponding sheath potential then produces an outward-pointing radial electric field. It can be shown that such a blob is driven unstable by its internal $\mathbf{E} \times \mathbf{B}$ rotation in the ideal MHD model. This effect may explain the fine structure observed in the hot blobs formed after large Edge Localized Mode (ELM) crashes. This work is part of a broader program to understand whether the various edge plasma regimes observed in different discharges (e.g. with and without ELMs) have some common physical elements.

Other work

Lodestar is involved in two collaborations intended to test the ideas of blob theory against the results of 3D simulations and experiments.

The best way to address the question of the turbulent origin of blobs is to study their emergence in 3D edge turbulence simulations. The theoretical tools are already in place for this study, e.g. the 3D edge turbulence code (BOUT) developed by Xu at LLNL.⁸ A collaboration is underway between LLNL and Lodestar to see whether the nonlinear coherent structures observed in the code have the properties predicted by the blob model.⁹

Experimentally, there is a rapidly growing database on spatial and temporal intermittency and convective transport by propagating coherent structures in the SOL plasma. This data was obtained using several diagnostics on a variety of linear and toroidal plasma devices, so it appears to represent a fairly universal and important phenomenon. As the theoretical models become more developed, it will become feasible to use the models and simulation codes to interpret the experimental data. Some preliminary work along these lines is underway in collaboration with the NSTX team.¹⁰

References

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8. X.Q. Xu, W.M. Nevins, R.H. Cohen, J.R. Myra, P.B. Snyder, [New Journal Phys. 4, 53.1 \(2002\)](#).
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Other References

Also see the slides from recent meeting presentations and a recent review paper:

- [Blob Stability and Transport in SOL Plasmas](#), D.A. D' Ippolito, J.R. Myra, S.I. Krasheninnikov, G.Q. Yu and S.A. Galkin, invited talk presented at the 2003 International Sherwood Fusion Theory Meeting, Corpus Christi, TX, April 28-30, 2003.
- [Blob Transport in the Tokamak Scrape-Off-Layer](#), D.A. D' Ippolito, J.R. Myra, D.A. Russell, S.I. Krasheninnikov, G.Q. Yu and A.Yu Pigarov, invited talk presented at the 2003 Plasma Edge Theory Meeting, San Diego, CA, Sept. 3-5, 2003.
- [Blob Transport in the Tokamak Scrape-Off-Layer](#), D.A. D' Ippolito, J.R. Myra, S.I. Krasheninnikov, G.Q. Yu and A.Yu Pigarov, review paper for the *Proceedings of the 2003 Plasma Edge Theory Meeting*, to be published in Contributions to Plasma Physics.

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