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Transport of plasma by convective, "bursty" processes is important in describing the scrape-off-layer (SOL) of tokamaks and other devices. The basic characteristics, physical mechanisms and dynamics of coherently convecting objects, *i.e.* "blobs", are described. The role of boundary conditions on blob filaments along the field line is emphasized. Blobs have been observed and analyzed in the BOUT 3-D turbulence code. It is argued that blob transport should be relevant to the density limit.

Edge and scrape-off-layer (SOL) transport processes are bursty or intermittent; substantial portions of the particle and energy fluxes are convective rather than diffusive; and these fluxes can be carried by relatively large coherent objects.[1-8] Gas-puff-imaging[3] diagnostics have enabled 2D movie-like visualization of these objects, here called "blobs",[6,7] which are filamentary along the magnetic field, B, and are localized to a scale of order 1 cm perpendicular to B. The blob's flux tube can contain substantially more plasma than its surroundings, so that blobs are strongly nonlinear, with $\delta n/n \sim 1$.

The transport of large coherent objects across the SOL of a tokamak is important. Fast convective transport can overwhelm the "normal" parallel flow of particle and energy along field lines into the divertor, affecting divertor and machine performance. Strong perpendicular particle transport to the walls can lead to regimes of main chamber recycling.[9] Furthermore, damage to plasma facing components by fast perpendicular convection is a serious concern in future burning plasma experiments. Turbulence generated blobs, and the possibly similar convection of ELMs in the far SOL, are of interest in this regard.

The complex turbulent processes that give rise to blob formation require large scale simulations for a quantitative description. In contrast, the dynamics of an isolated blob, and the mechanisms for blob-induced transport, are relatively simple and amenable to reduced modeling. Here, we outline some of the key physical ingredients.

When a force **F** acts on a blob, the species-dependent $\mathbf{F} \times \mathbf{B}$ drift can induce a charge polarization and an internal electric field **E**.[6,7] The resulting $\mathbf{E} \times \mathbf{B}$ drift propels the blob as a whole across the SOL, in the direction of **F** and provides a robust mechanism for convective transport. Curvature and grad-B drifts, considered explicitly here, cause an outward (increasing R) convection in the tokamak SOL. Similar physics has also been discussed for pellets.[10] Other forces (e.g. the neutral wind,[11] and the centrifugal force in a rotating plasma column) can play an analogous role. Many of the familiar linear instability drives in the SOL are known to have nonlinear dynamics which supports convective propagation of coherent meso-scale structures. In addition to the curvature drive considered explicitly here, the long wavelength, non-linear limit of the grad-T sheath and parallel velocity shear instabilities has also been analyzed.[12]

Charge accumulation, and therefore **E**, is mitigated by currents; thus, the rate of **E** × **B** convection is determined by the effective plasma resistivity and the path of current flow (Fig. 1). When the plasma resistance parallel to B, $\eta_{||}$, is small, $J_{||}$ flows along field lines to limiter sheaths which set the effective path resistance through the sheath voltage-current relationship $J_{||} = nec_s\{1-\exp[-e(\Phi-\Phi_B)/T_e]\}$. In addition to the current and potential "dipole" induced by the blob's "monopole" structure in pressure, the net charge ambipolarity of the blob requires a Bohm sheath potential $\Phi_B \sim 3T_e$ on each field line. For "hot" blobs having an internal temperature profile $T_e(r)$ (where r is the local blob coordinate) there will be a corresponding "monopole" $\Phi_B(r)$. This electric field will cause the blobs to spin about their axis, mixing and reducing the induced charge separation[13]. The competition between these effects is described by the vorticity equation for the potential Φ

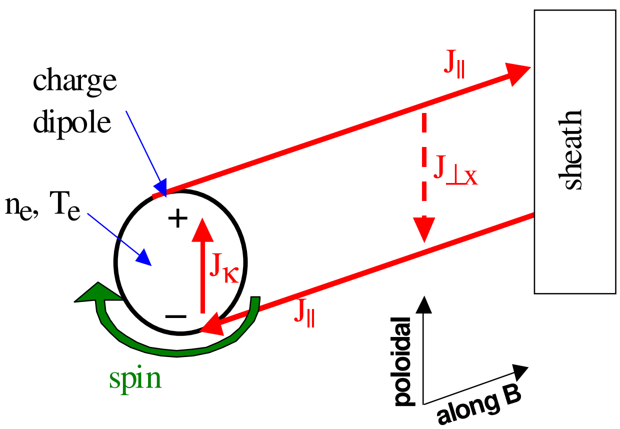


Fig. 1 Curvature-induced charge polarization; current loop paths for draining, and mixing.

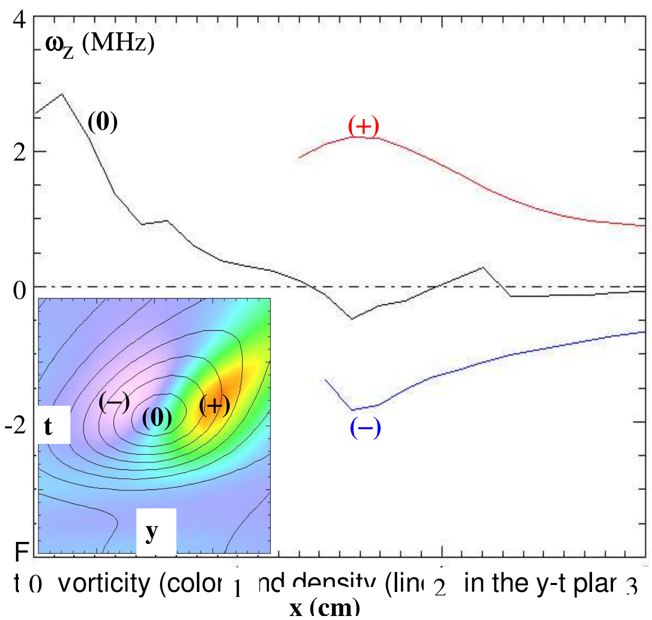
$$\frac{c^2}{4\pi v_a^2}\frac{d}{dt}\nabla_\perp^2\Phi = \nabla_{||}J_{||} + \frac{2c}{B}\mathbf{b}\times\boldsymbol{\kappa}\cdot\nabla p \qquad (1)$$

with curvature $\kappa \approx \nabla \ln B$ and other notations standard.[7]

When $\eta_{||}$ is sufficiently large, perpendicular processes can "short circuit" the current loop before they reach the sheaths. Such processes have been shown to be especially effective in the vicinity of X-points, where the strong elliptical fanning of the flux tubes enhances charge transport (i.e. perpendicular conductivity) across the thin part of the fan.[14] This results in blobs with a 3D structure which are disconnected from the end sheaths. In the 2D connected limit, the vorticity equation may be integrated along the field lines, using the sheath voltage-current relationship as a boundary condition on $J_{||}$. For 3D blobs, a similar procedure may be applied, taking into account the disconnection in the vicinity of an X-point.[15] Above a critical blob β, field line bending becomes important. In this regime, outgoing Alfvén waves can be used to provide another effective parallel boundary condition for $J_{||}(\Phi)$.[10,14]

Analytical and numerical studies show that blob evolution is affected by "secondary" blob instabilities.[16,17] In the simple 2D sheath connected case for thermalized [T(r) = const, non-spinning] density blobs, there is a window of effective blob radius: $a \sim a_*$ where a_* is the scale for which the inertial, sheath and curvature terms balance in the vorticity equation. Coherency is maximized for objects of this scale – they persist for many convection times. Smaller blobs, $a < a_*$, are dominated by the inertial (vorticity advection) term and are subject to strong Kelvin-Helmholtz instabilities, while larger blobs $a > a_*$ bifurcate due to nonlinear evolution of the curvature-driven instability. Spinning blobs are also subject to rotational instability.[18] The existence of characteristic blob scales is significant for transport: each regime will have a scaling of ϕ and $v_x \propto \partial\phi/\partial y$ with a.

Simulations with the BOUT 3D turbulence code[8] in edge/SOL divertor geometry illuminate blob generation and propagation. Recently analysis[15] of an X-point fueled simulation at high density ($n_{sep} \sim 10^{13}$ cm^{-3}) has shown that: (i) blobs form as a nonlinear state of strongly driven 3D edge turbulence, (ii) blob disconnection occurs with increased parallel plasma resistivity due to neutral-fueling-induced X-point plasma cooling (iii) the strong turbulence and disconnection result in $e\phi/T \sim 1$ which implies rapid radial convection ($v_x \sim$ 1-2 km/s $\sim 0.1\ c_s$) that is consistent with X-point current loop closure by ion polarization currents.



Blobs are easily diagnosed in BOUT as a correlation of monopole density and dipole vorticity structures that persist for long times and convect radially outward. An example is shown in the inset of Fig. 2, in the y (poloidal) – t (time) plane for x near the simulation boundary ("wall"). The figure shows the history (vs. radial position x riding with the blob) of the monopole (0) and dipole (±) components of vorticity $\propto$ charge. Blob convection occurs when the spin (0) decays, allowing a strong dipole to form.

The competition of fast radial convection with the normally dominant parallel transport processes may be important in understanding the density limit. When the plasma along the field lines and near the divertor plates is hot, and not too collisional, the parallel energy transport channel is dominant. Sheath-connected hot blobs will spin, further mitigating charge polarization and reducing perpendicular relative to parallel transport. When the parallel energy transport channel is dominant, the plasma remains hot, and not too collisional, along the field lines and near the divertor plates. In the opposite limit, cold collisional plasma near the plates causes blob disconnection, isolating the blob from the sheaths. This increases v_x, both by the reduction of spin and by the increased Φ that results from larger circuit resistance. The dominance of perpendicular over parallel transport prevents heating of the plasma near the plates, sustaining the state. When radial convection is strong, the edge T_e cannot be maintained, and eventually leads to the well known collapse of the current channel and MHD disruption. This picture shares some important features with experimental observations, which have established a link between edge transport[9] and in particular intermittent convective transport and the density limit,[19] and is consistent with edge transport modeling[20] in which increasing effective anomalous convection was inferred in approaching the density limit.

In conclusion, blobs provide a simple, robust and rather universal convective transport mechanism. There are a rich variety of blob regimes corresponding to various charge polarizing forces, and the mitigation of charge accumulation by different current paths. Parallel boundary conditions and collisionality play an important role in this description. From 3D simulations, we have shown that blobs arise naturally from tokamak edge turbulence, and that simple blob physics can describe many features of the observed dynamics. Further work in this area may shed light on the density limit[19] and recent density limit simulations.[21]

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