Blob Transport in the Tokamak Scrape-off-Layer

D. A. D'Ippolito, J. R. Myra, and D. A. Russell

*Lodestar Research Corporation, Boulder, Colorado*

S. I. Krasheninnikov, G. Q. Yu, and A. Yu. Pigarov

*University of California, San Diego, California*

**Acknowledgements**

G. Antar, J. Boedo, R. Macqueda, G. McKee,

W. Nevins, D. Stotler, D. Rudakov

J. Terry, X. Xu, S. Zweben

*Presented at the 9th International Workshop on Plasma Edge Theory in Fusion Devices, San Diego, California, September 3-5, 2003*
Motivation and Introduction

- growing experimental evidence that intermittent radial transport in the SOL can be explained by coherent, propagating structures (“blobs”).

- **two-scale structure** of SOL density profiles; non-diffusive in the far SOL (C-MOD, DIII-D, AUG)
- **wall recycling** dominates particle fueling in C-MOD
  \[ \Rightarrow \text{importance of convective transport in far SOL} \]
- diagnostic imaging & probe data on C-MOD, DIII-D, NSTX, Tore Supra, MAST, and PISCES
  (Zweben, J. Terry, Maqueda, Antar, Boedo, Rudakov, McKee, Labombard, Endler…)
  - **turbulence** \[ \Rightarrow \text{propagating coherent structures} \]
  - **responsible for large fraction of SOL transport**
  - **non-Gaussian statistics similar on all machines** (Antar, Boedo)
  - **correlated with ELMs** (Boedo, Endler)

- simple theoretical models of blob propagation and decay exhibit some of the qualitative features seen in the experiments.

- recent simulations extend these models to include blob dynamics and interaction with the background plasma.
UEDGE simulations of DIII-D provide evidence of convective transport

- include time-independent cross-field convective velocity $V_{\text{conv}}$ in 2D edge transport code UEDGE
- analyze a series of DIII-D L-mode discharges having the same NBI input power but different average densities
  - need outwards $V_{\text{conv}}$ to match experimental profiles
  - $V_{\text{conv}}$ increases with density

\begin{itemize}
  \item $D_\alpha$ a.u. vs. $\langle n_e \rangle^3$
  \item $P_N$, mtorr vs. $\langle n_e \rangle^3$
  \item $V_{\text{conv}}$, m/s vs. $\langle n_e \rangle$
  \item $\Gamma_{\text{main}}/\Gamma_{\text{total}}$ vs. $\langle n_e \rangle$, $10^{13}$ cm$^{-3}$
\end{itemize}

$V_{\text{conv}} \ll v_{x,blob}$

Gas Puff & BES imaging shows blobs

GPI data on C-MOD
(S. Zweben, J. Terry, et al., APS 2001)

BES data on DIII-D
(Boedo, APS 2002)

Blobs are localized $\perp \mathbf{B}$, but extended along $\mathbf{B}$ field lines.
Probe signals on DIII-D show intermittent transport in L- and H-modes due to blobs

- conditionally-averaged signal shows *intermittent* events with *fast-rise and slow decay* in density and fluxes
- $E_0$ correlated with density and flux pulses
- blobs produced in all regimes (*also by ELMs*)

Blob transport similar on different machines; statistics are non-Gaussian

Ion saturation current shows similar intermittency on several machines (toroidal and linear)

- large events are blobs propagating outwards
- PDF of $I_{\text{sat}}$ is skewed towards positive events (non-Gaussian)
- PDF is similar on different machines

Characteristic Time Scales

- Estimate blob time scales for typical tokamak parameters
  
  blob radius: $a = 2 \text{ cm}$
  distance to wall: $w = 10 \text{ cm}$
  blob velocity: $u_x = 10^5 \text{ cm/s} = 1 \text{ km/s}$
  connection length: $L_{\parallel} = 600 \text{ cm}$

  \[ \tau_{\parallel} = \frac{L_{\parallel}}{c_s} = 200 \mu s \]
  \[ \tau_w = \frac{w}{u_x} = 100 \mu s \]
  \[ \tau_c = \frac{a}{u_x} = 20 \mu s \]

- Notes:
  
  - $\tau_w/\tau_{\parallel} \approx \frac{1}{2} \Rightarrow$ flattened profiles with plasma at wall
  - $\tau_c$ is comparable to the experimentally-measured autocorrelation times ($\approx 10 - 30 \mu s$)
Motivation and Introduction

- growing experimental evidence that intermittent radial transport in the SOL can be explained by coherent, propagating structures (“blobs”).
  
  - two-scale structure of SOL density profiles; non-diffusive in the far SOL (C-MOD, DIII-D, AUG)
  - wall recycling dominates particle fueling in C-MOD
    ⇒ importance of convective transport in far SOL
  - diagnostic imaging & probe data on C-MOD, DIII-D, NSTX, Tore Supra, MAST, and PISCES
    (Zweben, J. Terry, Maqueda, Antar, Boedo, Rudakov, McKee, Labombard, Endler…)
    o turbulence ⇒ propagating coherent structures
    o responsible for large fraction of SOL transport
    o non-Gaussian statistics similar on all machines (Antar, Boedo)
    o correlated with ELMs (Boedo, Endler)

- simple theoretical models of blob propagation and decay exhibit some of the qualitative features seen in the experiments.

- recent simulations extend these models to include blob dynamics and interaction with the background plasma.
Outline of Talk

• Analytic blob model

• Secondary instabilities and effect of background profiles
  ➢ "essential stability"
  ➢ 2D simulation results for curvature and velocity-shear instabilities
  ➢ rotational instabilities & ELMs

• Other topics
  ➢ Blob statistics
  ➢ Diagnostics for blobs in 3D codes
  ➢ Analysis of NSTX GPI blob data

• Assessment of blob model

• Summary and conclusions

Scope:

(1) focus on theory

(2) blob stability and transport
    (not turbulent origin of blobs)
Blobs move due to radial force

- net species-summed radial force $F_x$ ($\mathbf{b} \cdot \nabla \times \mathbf{F} \neq 0$) (curvature, centrifugal, neutral wind…)
- axial B field $\Rightarrow$ species-dependent $\mathbf{F} \times \mathbf{B}$ drift
- sheath or plasma resistivity $\Rightarrow$ charge polarization

- velocity $u_x$ of blob depends on blob radius $a$

$$ n(r) = n_b \exp \left[ - \left( \frac{r^2}{2a^2} \right) \right] + n_f $$

$$ n_f = 0 \quad \Rightarrow \quad u_x = q/a^2 \quad \text{where} \quad q = L||/R $$

- density \textit{blobs} move out to wall ($n_b > 0$),
- density \textit{holes} move in towards core ($n_f \neq 0, n_b < 0$)
Profiles depend on the blob size distribution

Ensemble average over power law distribution

\[ f(a) = a^{-p}, \quad a = \text{blob radius} \]

\( p = 1 \)

\[ \text{large blobs dominate transport for } p = 1, \quad \text{small blobs for } p = 4 \]

\( p = 4 \)


Small blobs travel faster and penetrate farther than large blobs
Outline

• Analytic blob model
• Secondary instabilities and effect of background profiles
  ➢ "essential stability"
  ➢ 2D simulation results for curvature and velocity-shear instabilities
  ➢ rotational instabilities & ELMs*

• Other topics
  ➢ Blob statistics*
  ➢ Diagnostics for blobs in 3D codes*
  ➢ Analysis of NSTX GPI blob data*

• Assessment of blob model
• Summary and conclusions

*work in progress
Study "secondary instabilities" of blobs

- Use far SOL model ($T = \text{const}$) described by the following equations

\[
\frac{d}{dt} \nabla^2 \phi + \nu \nabla^2 \phi = \frac{\alpha}{n} \phi - \frac{\beta}{n} \nabla y n
\]

\[
\frac{dn}{dt} = D \nabla^2 n - \alpha n
\]

\[
\frac{d}{dt} = \frac{\partial}{\partial t} + \nu \cdot \nabla = \frac{\partial}{\partial t} + b \times \nabla \phi \cdot \nabla
\]

$\alpha = (2\rho_s/L_{\|}) = \text{sheath parameter}$

$\beta = (2\rho_s/R) = \text{curvature parameter}$

$\nu = \text{viscosity}, D = \text{diffusion}$

Dimensionless: $\Omega_i \ dt \rightarrow dt, \rho_s \nabla \rightarrow \nabla, e\Phi/T_{es} \rightarrow \Phi, \nu/c_s \rightarrow \nu$, etc.

- Secondary "sheath-interchange" (SI) instability driven by internal blob pressure profile affects the radial velocity:
  - same force drives motion and instability ($\nabla B$)
  - SI instability [$\gamma \propto k_y^2 (\beta/\alpha L_{nx})$] breaks up blobs
  - smaller fragments move faster, increasing transport

(The global SOL version of this instability was studied by Nedospasov 1989, Garbet et al. 1991, Endler et al. 1995.)
Competition between stability and transport determines maximum blob size

- linear growth rate $\gamma$ for 1D "poloidally-elongated blob" ($y_b >> x_b$)
- transport rates for blob of radius $a = x_b$
  - diffusion rate $\gamma_d = D/a^2$ << other rates
  - convection rate $\gamma_c = u_x/a = q/a^3$
  - transport rate to wall $\gamma_w = u_x/\Delta x$, let $\Delta x \approx 10a$


- "essential stability" for $\gamma < \gamma_w \Rightarrow a < a_1$
- lower bound on $u_x$: $u_x > q/a_1^2$
- $a_2/u_x$ ⇒ maximum expected autocorrelation time
Nonlinear instability breaks up blobs

- 2D simulations ⇒ nonlinear evolution of instability can cause blob to bifurcate


\[ t/\tau_c: (a) 0, (b) 6, (c) 9, \text{ and (d) 12}; \quad n_f = 0.01, D = 0.005, \text{ and } a_s = 7. \]

- characteristic blob deformation before bifurcating
Effect of background density on blobs (1)

With small background:
- blobs move faster
- blobs are unstable

Background density:
- slows and stabilizes
- changes blob shape
  + steep leading edge
  + trailing wake


The blob equilibrium, stability and transport depends on the blob height above the background.
Effect of background density on blobs (2)

- Simulations show
  - strong effect of background on radial velocity $u_x$
  - dependence of $u_x$ on blob size:

![Graph showing the effect of background density on radial velocity](image)

$D'\text{Ippolito and Myra, Phys. Plasmas 2003}$

- blob slows down before bifurcation and speeds up afterwards (consistent with analytic model)
- blob accelerates down the SOL density profile
Effect of background density on blobs (3)

- blob in vacuum \(\Rightarrow\) uniform \(u_x\)
- blob on background \(\Rightarrow\) vortex flow pattern

Contours of density (solid) & flow (dashed) in lab frame

- sheared flow drives KH instability,
  \[ \gamma \propto \frac{v_x}{L_y} \]
- gives steep leading edge and trailing wake
- shape \(\Rightarrow\) qualitative agreement with probe data

\[ n_f = 0.5 \]

Numerical

Gaussian
Small blobs are unstable to Kelvin-Helmholtz instability

\[ a = 0.6 \text{ cm} \quad \text{(smaller blobs are more unstable to K-H)} \]

\[ a = 0.9 \text{ cm} \]


[Blob steepening and K-H also studied by Bian et al., (2003), and in ionospheric context by Guzdar et al., (1998)]
Density dips and impurity transport

Evolution of density dip with $a = 1.2$ cm, small $D = 0.01$


- density dips /holes propagate *inwards* from wall to core
- provides mechanism for enhanced impurity transport
- dips are unstable to secondary K-H instability
ELMs, Blobs and Rotational Instabilities

- ELMs ⇒ density and temperature pulses propagating to the wall (JET, AUG and DIII-D)
- Pulses have blob-like behavior (outwards convection, steep leading edge, etc.) but have more fine structure.
- Is fine structure due to rotational instabilities?

Blob rotation

Blob theory needs to be generalized to include temperature and Bohm sheath potential ($\Phi \approx 3T_e$) effects on blob dynamics

- background $T(x)$ ⇒ poloidal drift
- internal $T(r)$ ⇒ blob rotation

Blob rotation can drive rotational instabilities [see D'Ippolito et al., APS-DPP (2003)]

- centrally-peaked $T(r)$ ⇒ $E_r > 0$
  ⇒ centrifugal and Coriolis terms are destabilizing

(Freidberg and Pearstein, Phys. Fluids 1978)

- rotational growth rate $\gamma_R \sim 1/a^2$ exceeds $\gamma_{KH} \sim 1/a^3$ for $a >> 1$ and $\gamma_{SI} \sim m^2/a^2$ for mode number $m < m_{crit} \sim a^{1/2}$ [shaded region below]:

\[ \gamma_R \quad \gamma_{SI} \quad \gamma_{KH} \]

\[ 1 \quad a^{1/2} a^2 \quad a^{1/2} \quad m \rightarrow \]
Outline

● Analytic blob model
● Secondary instabilities and effect of background profiles
  ➢ "essential stability"
  ➢ 2D simulation results for curvature and velocity-shear instabilities
  ➢ rotational instabilities & ELMs*
● Other topics
  ➢ Blob statistics*
  ➢ Diagnostics for blobs in 3D codes*
  ➢ Analysis of NSTX GPI blob data*
● Assessment of blob model
● Summary and conclusions

*work in progress
Blob transport leads to non-Gaussian statistics

[see Myra et al., APS-DPP( 2003)]

- analytic model of periodic blob train passing a probe:

\[ n(t) = n_0 \exp \left[ \xi \left( \sin \frac{2\pi t}{\tau} - 1 \right) \right] \]

\[ n(t)/n_0 \text{ for } \xi = 1 \quad \text{and} \quad n(t)/n_0 \text{ for } \xi = 100 \]

- specific predictions about density statistics as \( \xi \uparrow \): (mean↓, skewness↑ but standard deviation \( \sigma \) is not monotonic in \( \xi \)). NSTX GPI data shows similar behavior:

red→blue→green ⇒ increasing x
Using GKV to diagnose blobs in BOUT simulations

D.A. Russell, J.R. Myra and D.A. D’Ippolito (Lodestar)
W.M. Nevins and X. Xu (LLNL)

[see Russell et al., APS-DPP (2003)]
Comparison of NSTX turbulence data with blob theory: extracting $n_e, T_e$ from GPI intensity

see Stotler et al. (this meeting)
Myra et al. (APS/DPP 2003, Albuquerque)

Gas Puff Imaging data from S. Zweben and R. Maqueda

$\Rightarrow$

$\Rightarrow$

cuts across the frames: equilibrium dashed, blobby solid
Assessment of the Blob Model

Some *qualitative* features of the experiments emerge naturally from the analytic blob model and the corresponding numerical simulations:

- *robust* mechanism for convective plasma transport
- two scale density and flux profiles
- faster decay of $T(x)$ than $n(x)$
- critical particle flux for ionization-sustained equilibria
- mechanism for inward transport of impurities
- shape of propagating pulses
- intermittency and non-Gaussian statistics
- possible mechanisms for the density limit and for fine structure in ELMs?

A more *quantitative* comparison with experiment requires further development of both the theory and the measurements:

- include $T(x,y)$, sheared $v_x$ and $v_y$, and rotation in 2D simulation codes
- include blob variation along $B$ (at high density)
- use 3D turbulence codes (e.g. BOUT) to study blob formation; develop new code diagnostics for blobs
- *dedicated experiments in SOL transport*: coordinate complementary diagnostics to simultaneously measure all parameters needed for theory
Summary

• Blob transport provides a robust mechanism for explaining the observed intermittency and radial transport in the far SOL.

• Blob motion is driven by a net radial force giving species-dependent drifts:
  - grad-B due to toroidal curvature (tokamaks)
  - centrifugal force (linear machines like PISCES)
  - neutral forces, e.g. "neutral wind" in LAPD [S. Krasheninnikov, PoP 2003]

• Radial convective flux of plasma depends on
  - blob size distribution
  - blob height above background density
  - ionization of neutrals (not discussed here)

• SOL convective transport has important implications for tokamaks
  - "main chamber recycling regime" ⇒ reduced divertor efficiency (Umansky et al., 1999; Pigarov et al., 2002)
  - may be related to the density limit on C-MOD (Greenwald, 2001; Xu, 2002; Myra et al., 2002)
Supplementary slides
(background material)
Effect of plasma resistivity on blob motion

- Sheath conductivity term ($\propto \alpha$) + curvature drift term ($\propto \beta$) balance in the vorticity equation to give the blob potential induced by charge polarization

$$\varphi = \frac{\beta}{\alpha n} \nabla y n = \frac{L}{R n} \nabla y n$$

- Plasma resistivity $\eta = m_e v_e / n e^2$ enhances the blob potential and increases its radial velocity

$$\varphi \rightarrow \left( 1 + \frac{m_e L}{m_i c_s} \right) \frac{L}{R n} \nabla y n$$

- Thus, plasma resistivity allows blob motion inside the separatrix and adds to sheath resistivity in SOL.

- Is plasma resistivity in SOL related to the density limit? (Xu, 2002)
Blob propagation due to "neutral wind"


Outwards radial force due to imbalance between the friction of the fast neutrals from the core and the slow neutrals from the wall $\Rightarrow$ radial blob motion.

Force:

$$F_{Ni} = \mu_{Ni} n \left\{ (N\nu)_{\text{fast}} K_{\text{fast}} + (N\nu)_{\text{slow}} K_{\text{slow}} \right\}$$

($K =$ neutral-ion collision rate)

Resulting outwards velocity:

$$v_x \propto N\nu_{\text{fast}} \left( \frac{K_{\text{fast}} - K_{\text{slow}}}{\Omega_t} \right) \frac{L_\parallel}{y_b^2}$$

Estimate $v_x \approx 10^5$ cm/s for LAPD parameters in agreement with experiment.
Stability and transport boundaries
vs normalized D and ν

If the inertial term in the vorticity equation is negligible, the blob radius \( a \) can be scaled out of the equations; the equations are invariant under the transformation:

\[
D \rightarrow a D, \quad a_s \rightarrow a_s/a, \quad \gamma \rightarrow \gamma a^3,
\]

\[
\varphi \rightarrow a \varphi, \quad n \rightarrow n
\]

![Graph showing stability and transport boundaries](image-url)
Physics and scaling of K-H instability

- Kelvin-Helmholtz instability is driven by velocity shear in vorticity inertial term

\[ \frac{d}{dt} \nabla^2 \varphi = 0 \Rightarrow \gamma_{KH} \sim k_x v_x \leq \frac{v_x}{L_y} \]

- Blob flow pattern with velocity shear requires substantial background density.

- Compare scaling of K-H growth rate with that of sheath-interchange mode

\[ \gamma_{KH} \sim \frac{v_x}{L_y} \sim \frac{1}{y_b^3}, \quad \gamma_{SI} \sim \frac{k_y^2}{L_x} \sim \frac{1}{x_b^3} \]

- Note that \( \gamma_{KH} \) and \( \gamma_{SI} \) have opposite dependences on blob shape

  - \( \gamma_{KH} \) larger when \( x_b \gg y_b \)
  - \( \gamma_{SI} \) larger when \( y_b \gg x_b \)
Reduction in blob velocity by K-H instability

2D Simulations by Yu et al. (2002) show that the radial blob velocity $V_b$ decreases for small blobs due to the Kelvin-Helmholtz instability:

\[ V_b \cdot \delta^2 \]

Normalized $V_b \cdot \delta^2$ of blobs with $\delta_x = \delta_y = 0.6\text{~cm}$

(Notation: $V_b = u_x$, $\delta = a$)