Physics of drifting sub-pulses in radio pulsars

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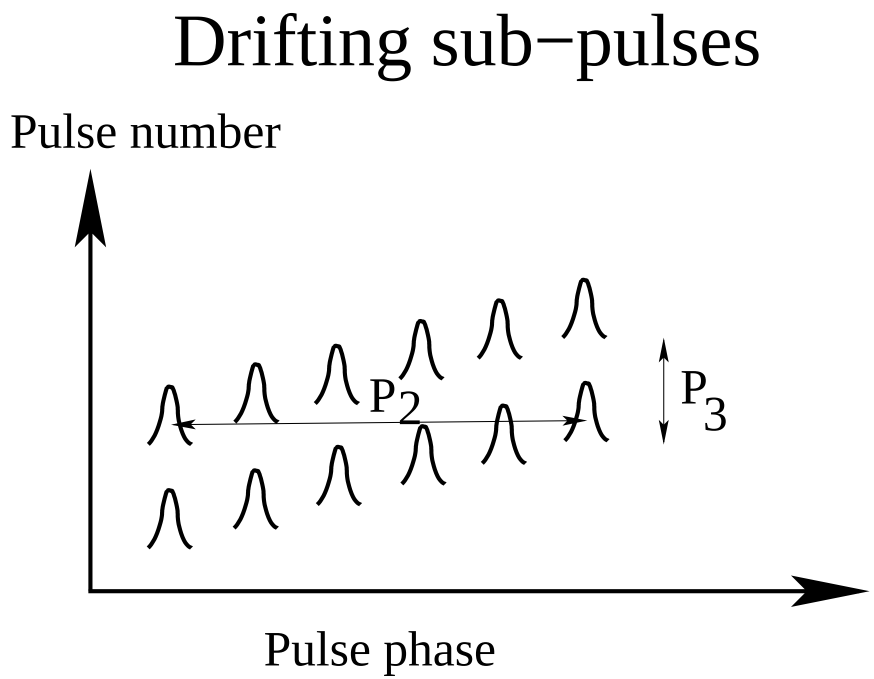
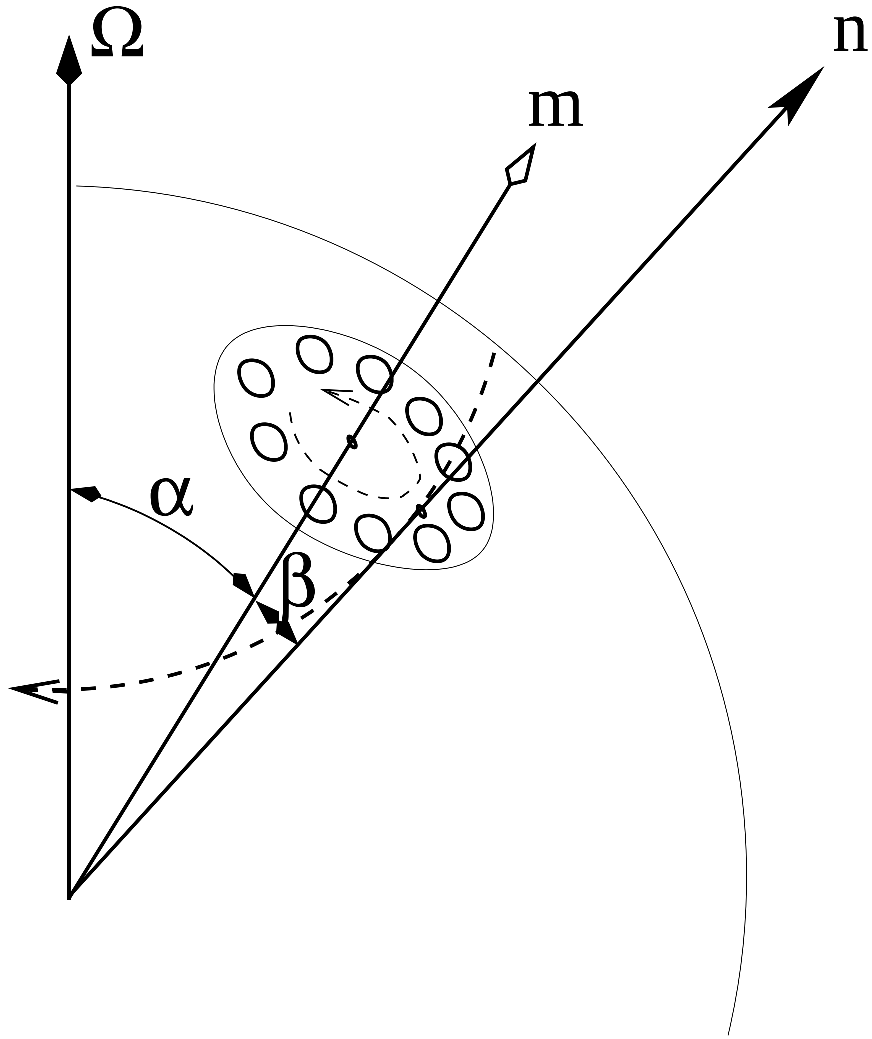
Observations modeled

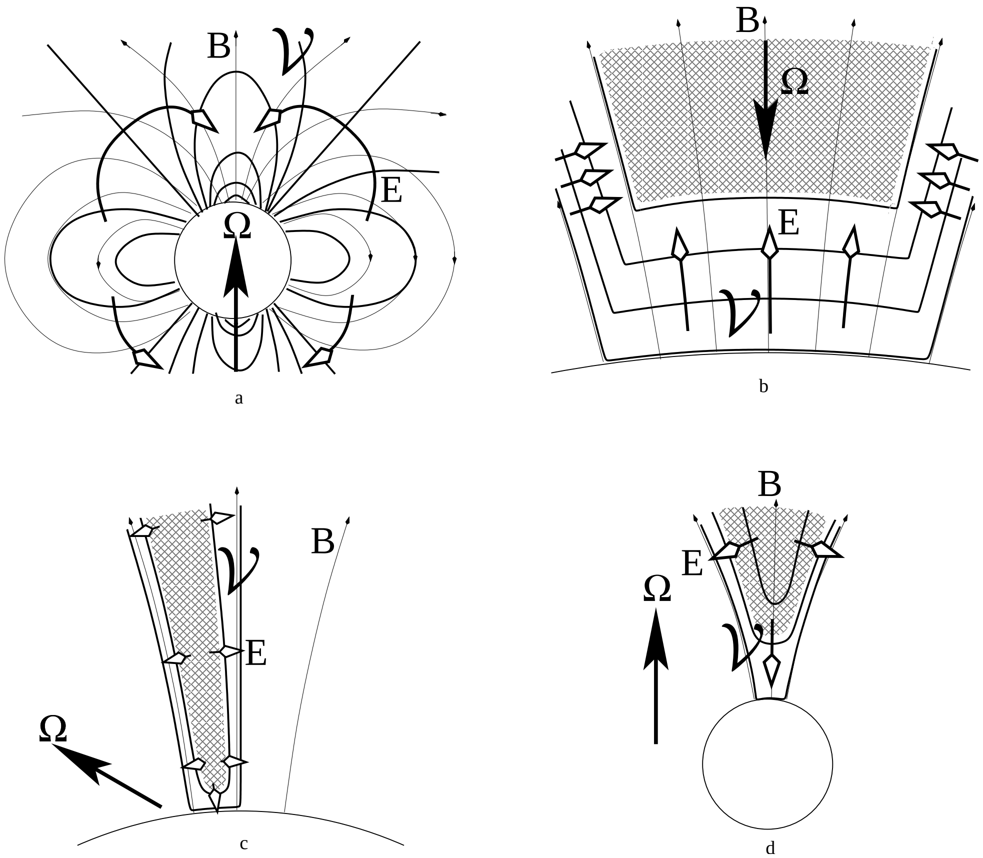




What we have learned from single pulse studies:

- stable rotation of emission carousel around magnetic axis;
- global electric circuit determines emission & mode changes.

Pulsar models



In common:
Voltage source,
electric + return circuit,
pair plasma

$$E_{\|}(r_* + r_{pc}) \approx -pcB_* \left(\frac{\Omega_* r_*}{c}\right)^q$$

Various models for pair creation (hatched) on the open field lines:

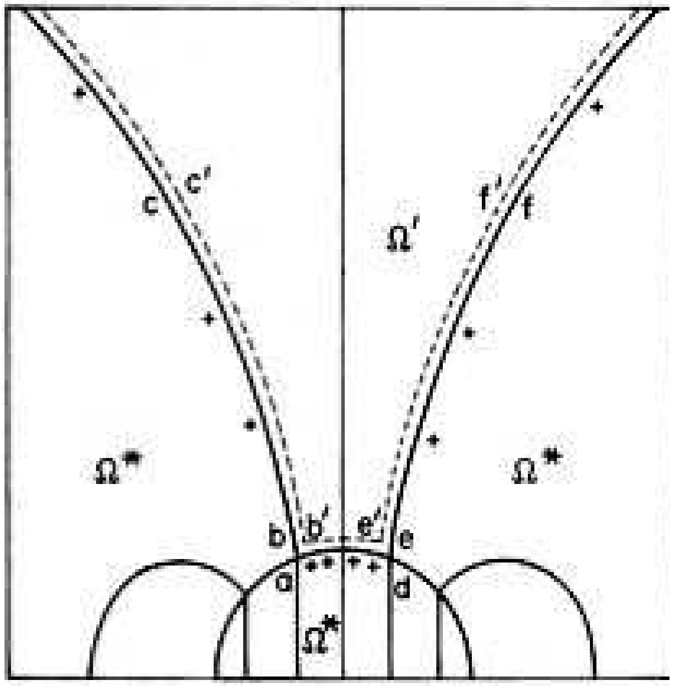
a. Deutsch 55 {p,q}={1, 1}; b. RS75 {-2, 1.5}; c. Arons 83 {0.5, 2.5};

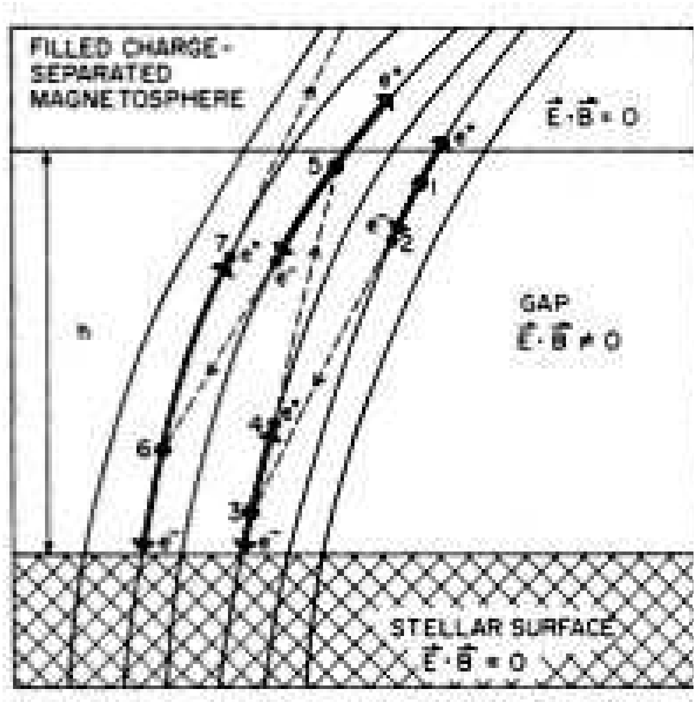
d. Muslimov & Tsygan 92 {1, 2}

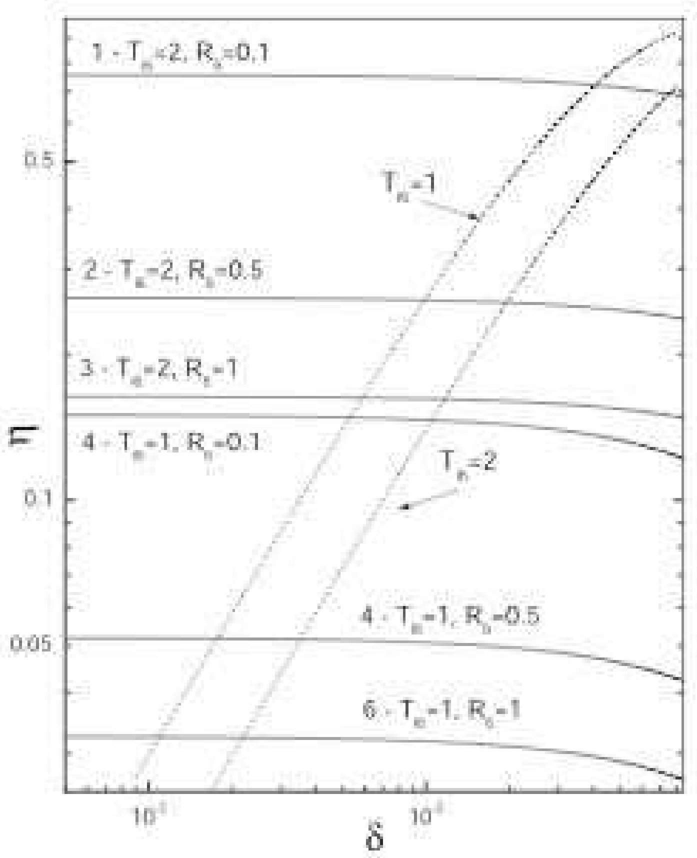
Drifting sub-pulses: Models

- Ruderman & Sutherland 1975; Gil et al. 2003: vacuum gap partially screened due to thermoionic emission
- Clemens & Rosen 2004: non-radial pulsations of ns; exclusive selection of $m = 0, l \sim 500 - 700$ spherical mode; link to emission?
- Kazbegi et al. 1991; Gogoberidze et al. 2005: drift wave electric field modulates distribution function or changes emission angle; requires weak B.
- Wright 2003: due to constructive interaction between upgoing e^- and downgoing e^+ beams between inner and outer acceleration gap.

RS75; Gil et al. 2003

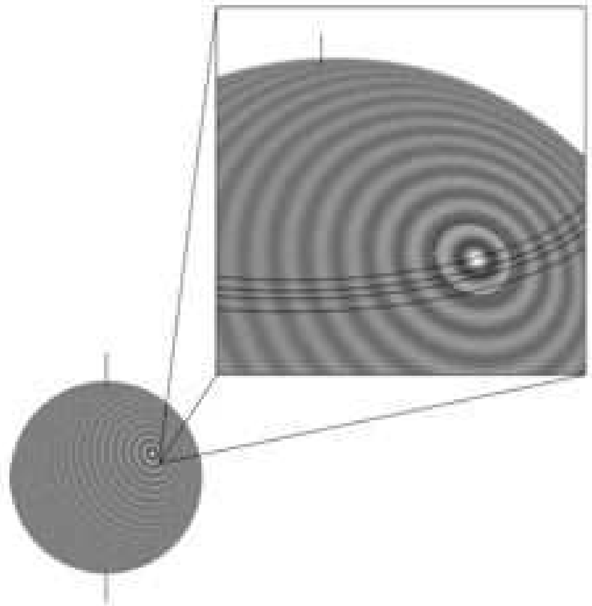


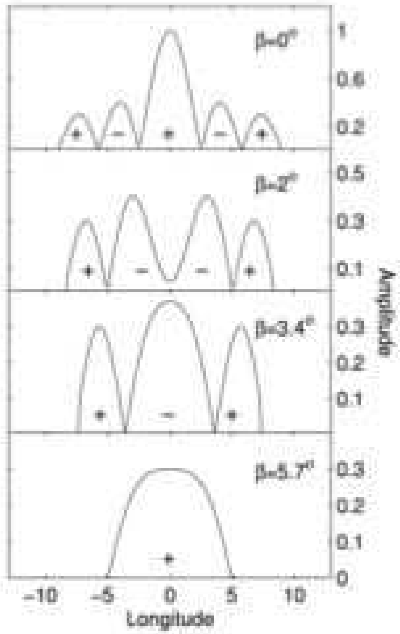


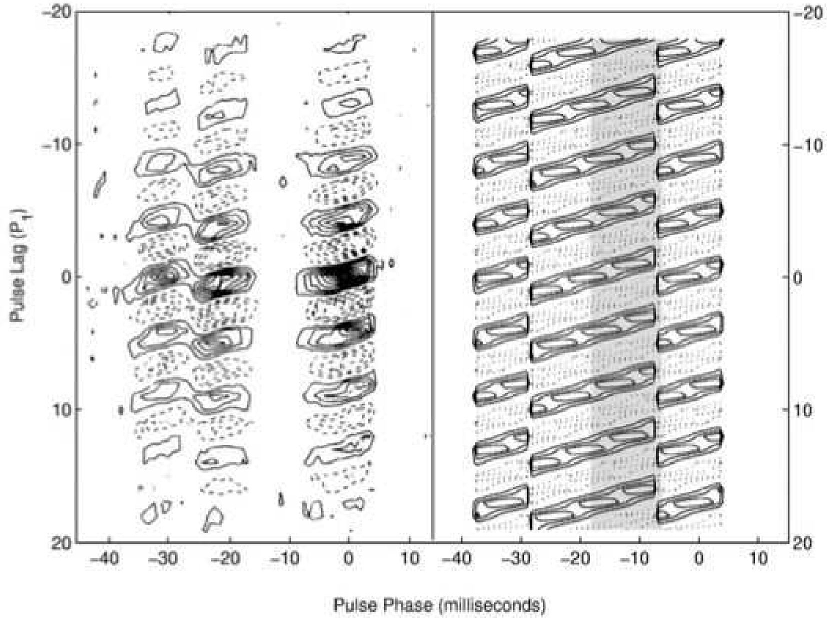


Vacuum gap Sparks $\boldsymbol{E} \times \boldsymbol{B}$ drifting Reduction potential gap

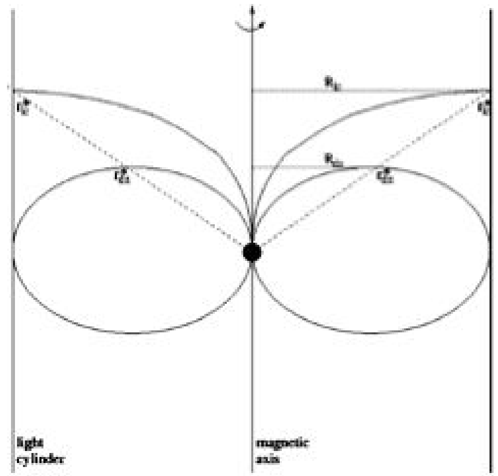
Clemens & Rosen 2004

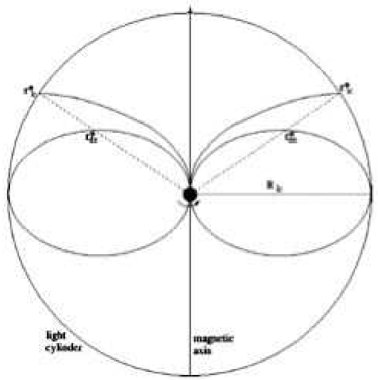


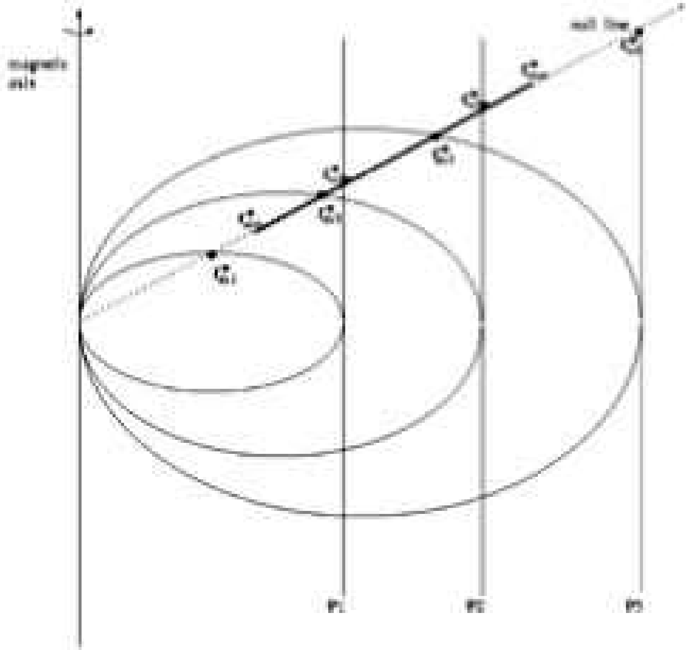


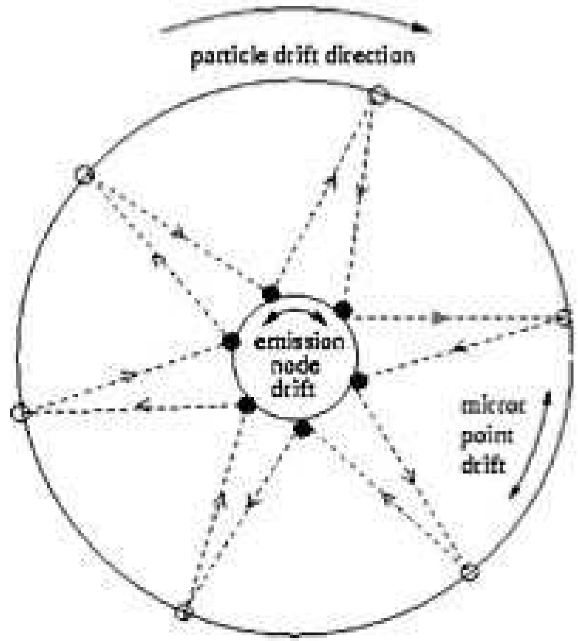


Wright 2003

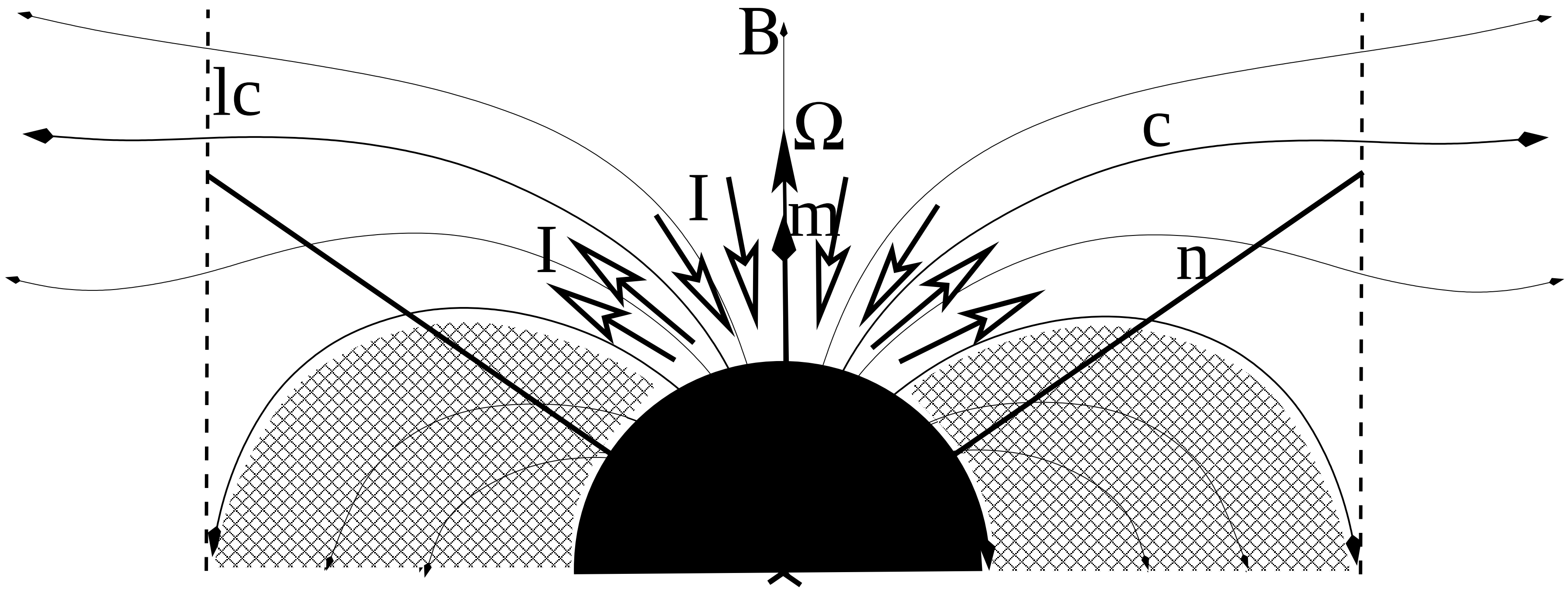

light
cylinder
magnetic
axis






particle drift direction
emission
node
drift
mirror
point
drift

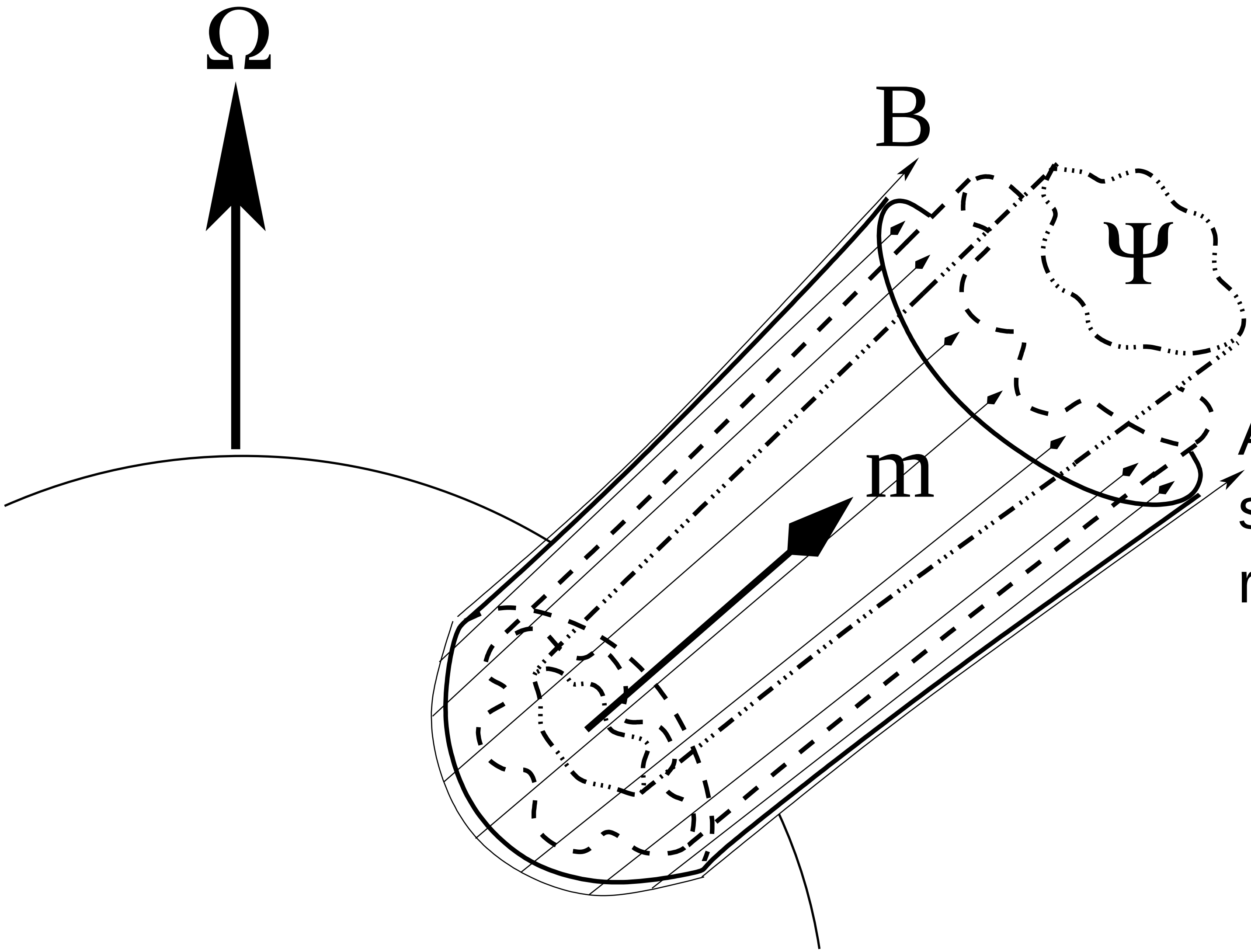
Current system: aligned rotator



$\theta_c = \theta_{pc}(2)^{-0.5} = 0.96\theta_n$ cf.Wright!

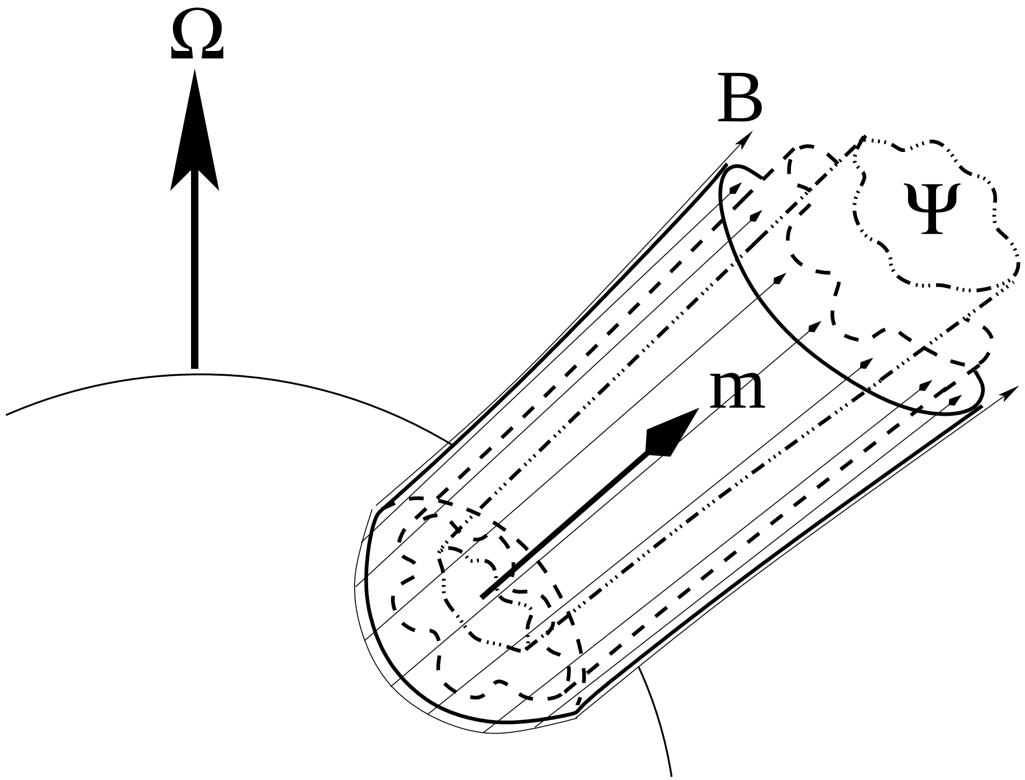
$\theta_n = \theta_{pc}(2/3)^{1.5}$

Electrostatic potential in comoving frame: oblique rotator



Assumed: stationary in rotating frame

Electric potential in comoving frame; oblique rotator



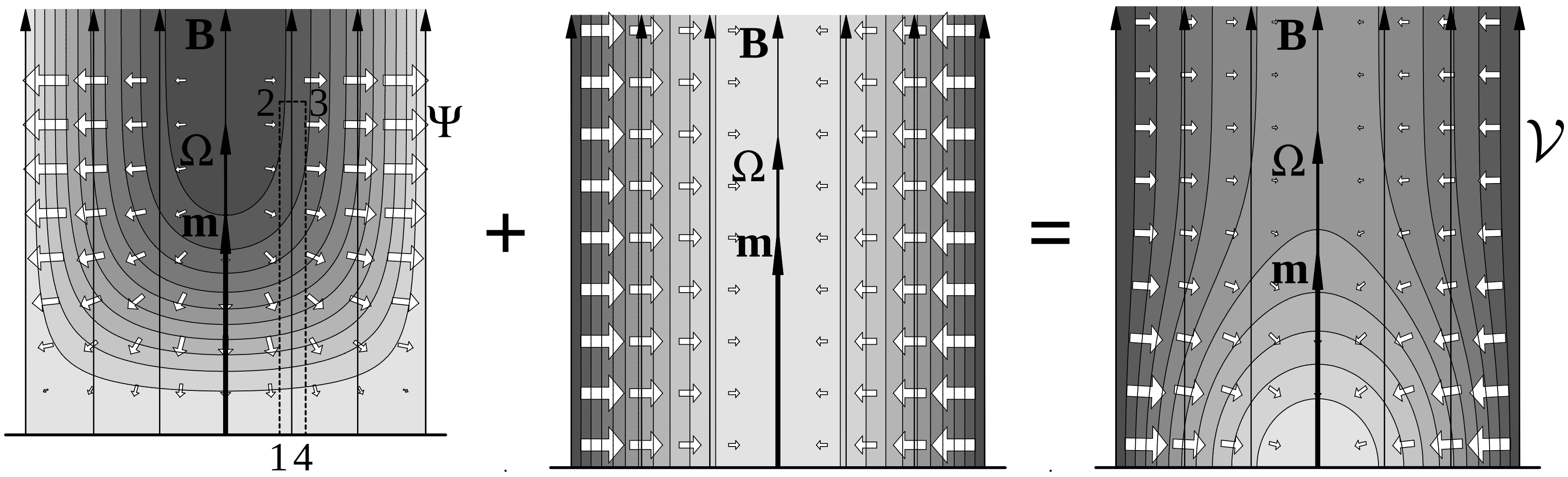
$$\mathbf{E} = -(\Omega_* \times \mathbf{r}) \times \mathbf{B} - \nabla\Psi$$

(1) $$\mathbf{v} = \Omega_* \times \mathbf{r} + \mathbf{u},$$

(2) $$\mathbf{u} = -\frac{\nabla\Psi \times \mathbf{B}}{B^2}.$$

Sketch is for ideal MHD above non-ideal rupture zone at foot-points

Electrostatic potentials for aligned rotator + axial symmetry

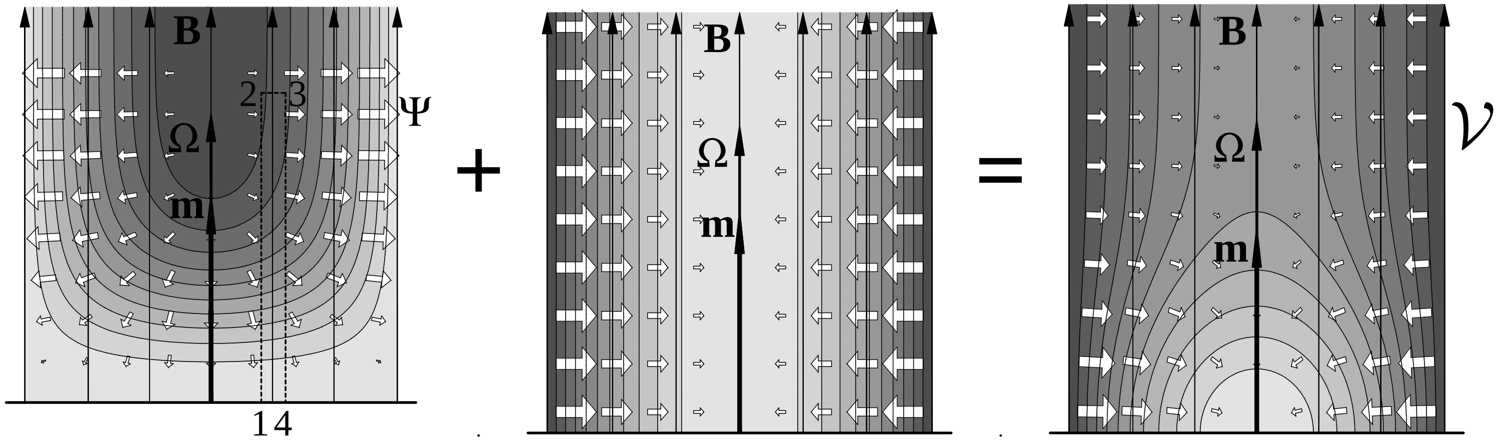


Star frame $-\nabla\Psi$ **Rigid rotation** $-(\Omega_* \times \mathbf{r}) \times \mathbf{B}$ $=$ **Lab frame** $-\nabla\mathcal{V}$

Note:

- slippage at foot-points due to parallel electric field,
- 'rupture' of field lines,
- generalized magnetic reconnection,
- dissipative element of electric circuit.

Electrostatic potentials for aligned rotator + axial symmetry



Star frame **Rigid rotation** **Lab frame**

Above the acceleration region, $E_\parallel = 0$ and $\boldsymbol{E}$ due to space charge of beam, not to stellar surface charge!

$$\mathcal{V}_\parallel(R) = \int_1^2 E dl \rightarrow E_\perp(R) = -\frac{\partial}{\partial R}\mathcal{V}_\parallel(R)$$

$$\mathbf{E}+\mathbf{v}_\alpha\times\mathbf{B} = 0 \rightarrow v^0_{\alpha\phi} = -\frac{E^0_R}{B_0}+v^0_{\alpha z}\frac{B^{\mathsf{S}}_\phi}{B_0}$$

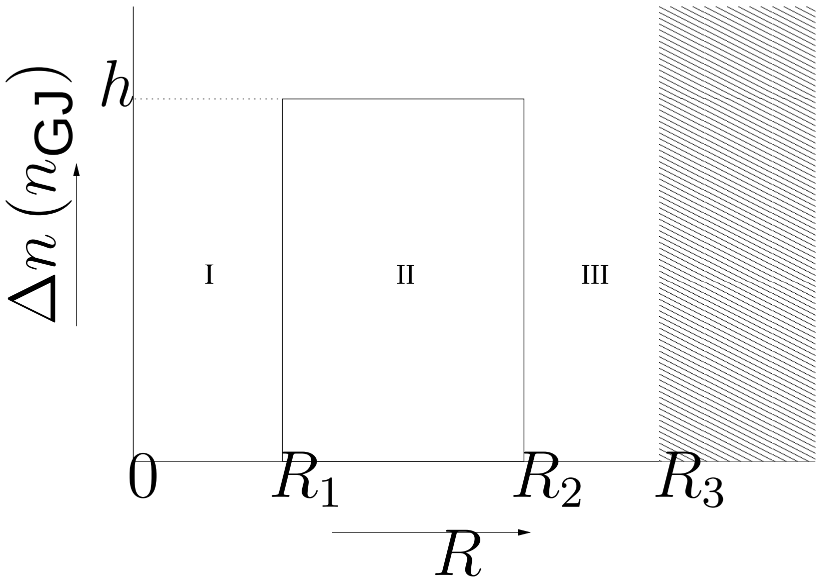
$E\times B$ drift modified by magnetic self-field from current-carrying beam:

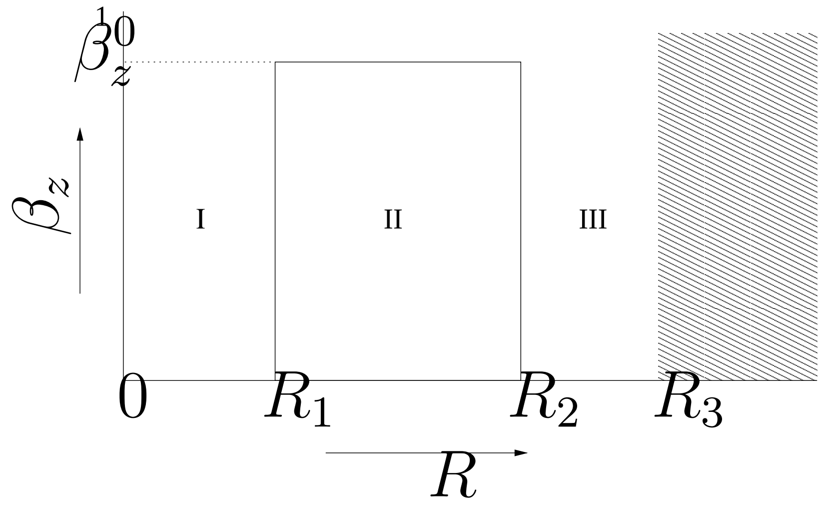
for charge-separated beam $v^0_{\alpha\phi} = -\frac{E^0_R}{\gamma^2_\alpha B_0}$

Differential rotation: diocotron or electrostatic KH instability
rotational shear, slipping stream instability

Non-neutral, cold, relativistic pair plasma, $E_{\|} = 0, B$ uniform

Beam configuration 1





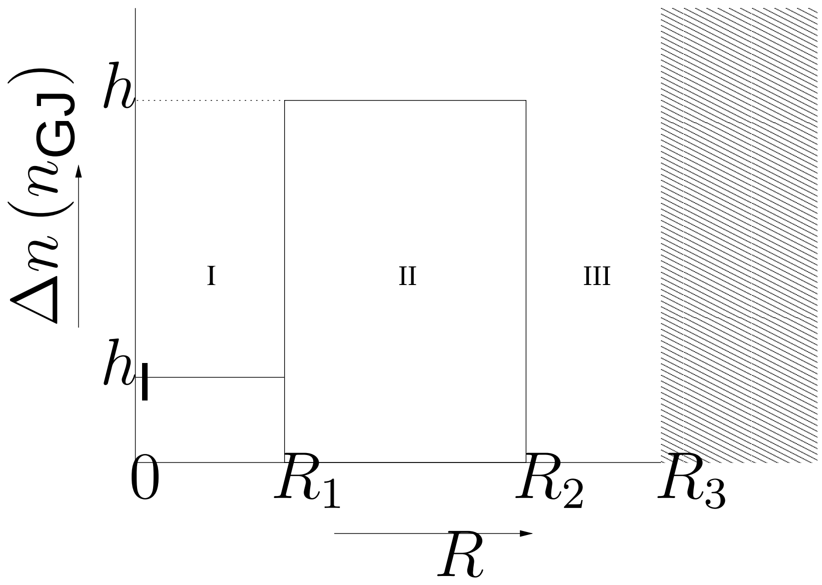
$J_z(R) = f(R)\beta_z^0(R) e n_{GJ}$

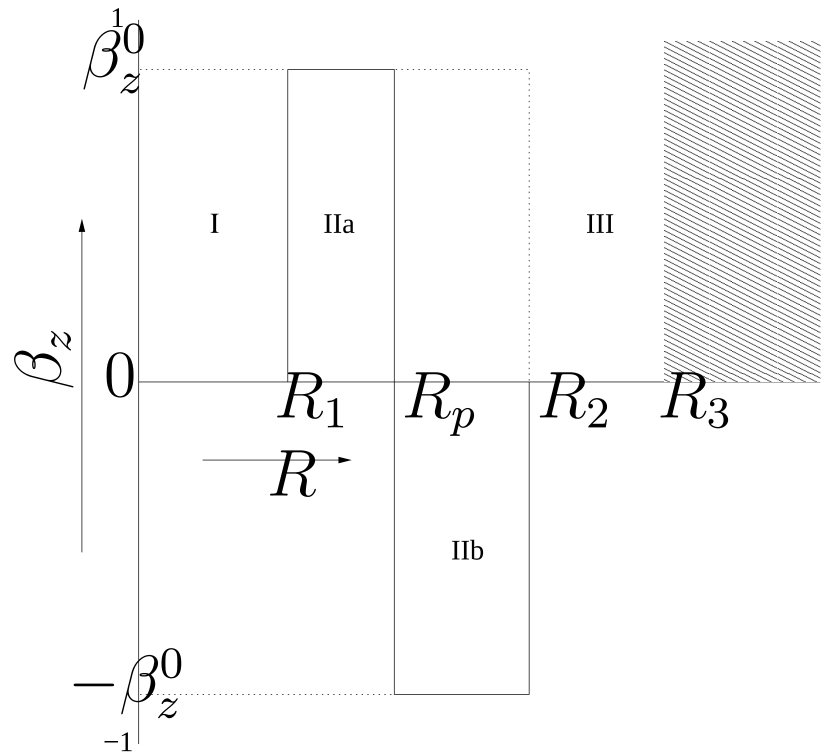
h: charge density excess; f: current density excess factor.

hollow beam

Differential rotation: diocotron or electrostatic KH instability

Beam configuration 2 & 3

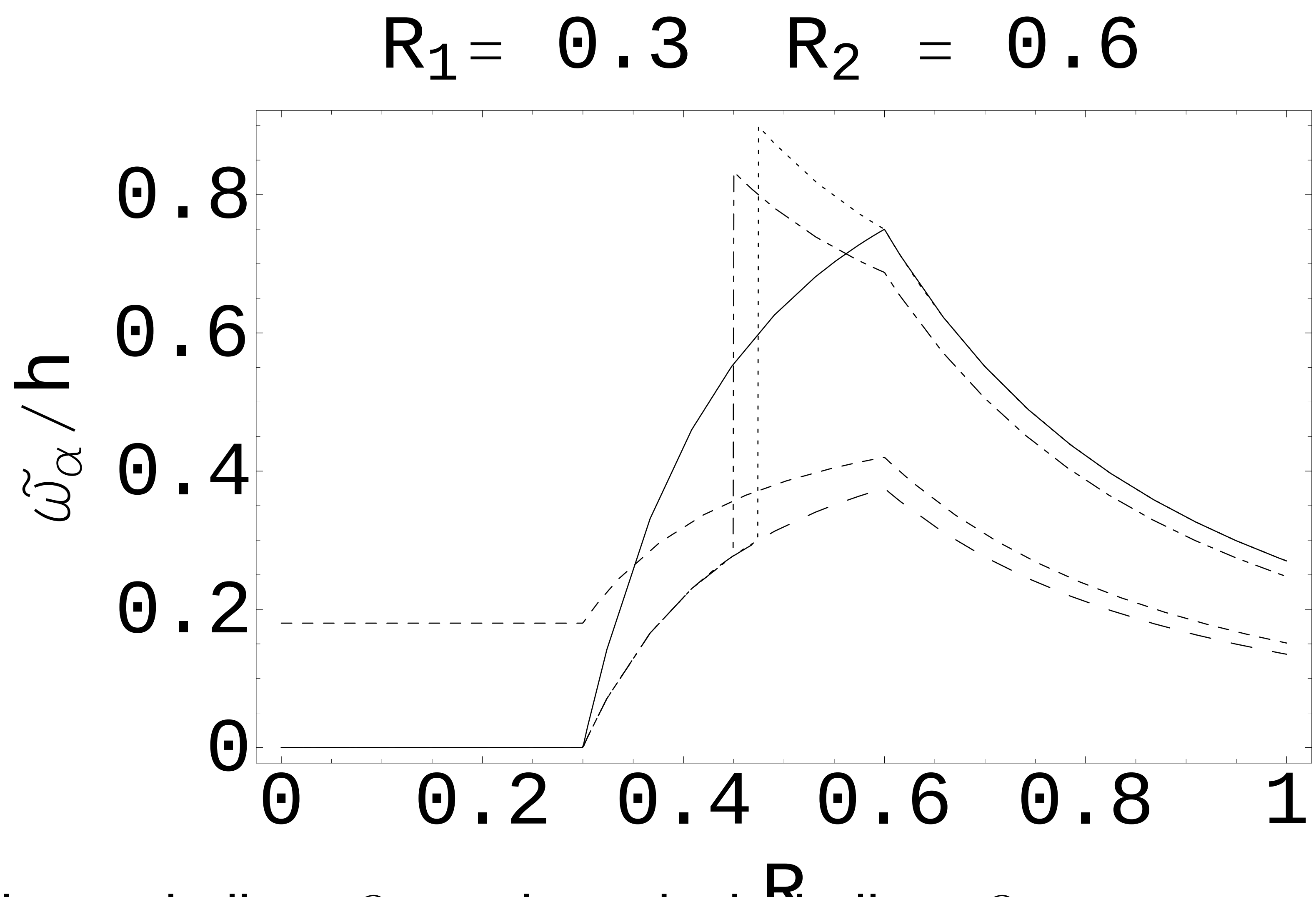




core component present

reverse current present

Equilibrium rotational velocities: examples

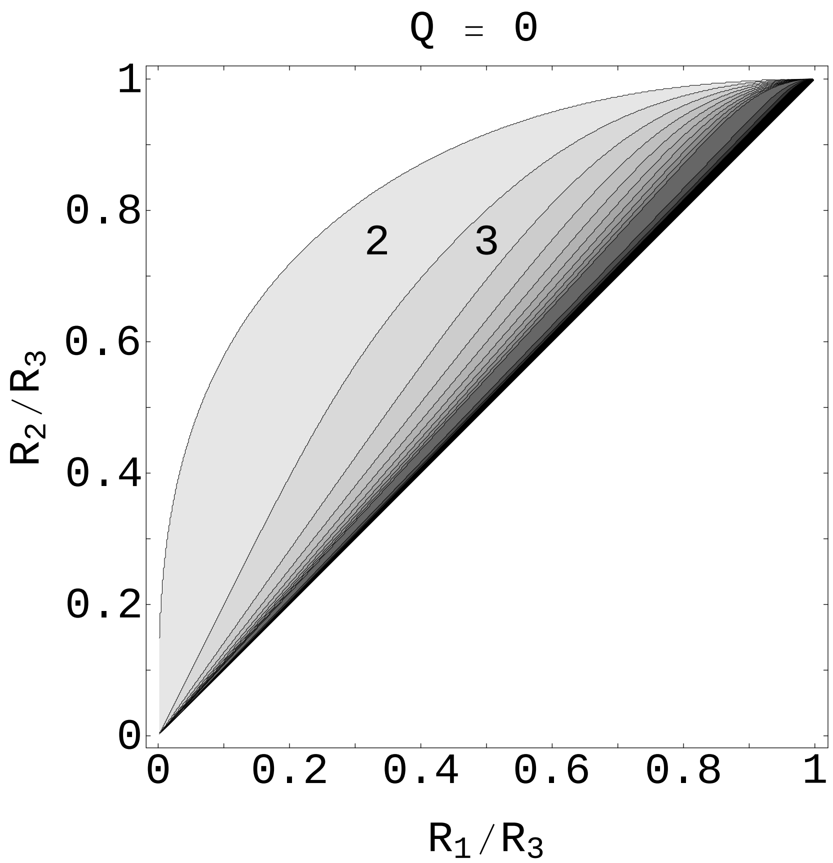


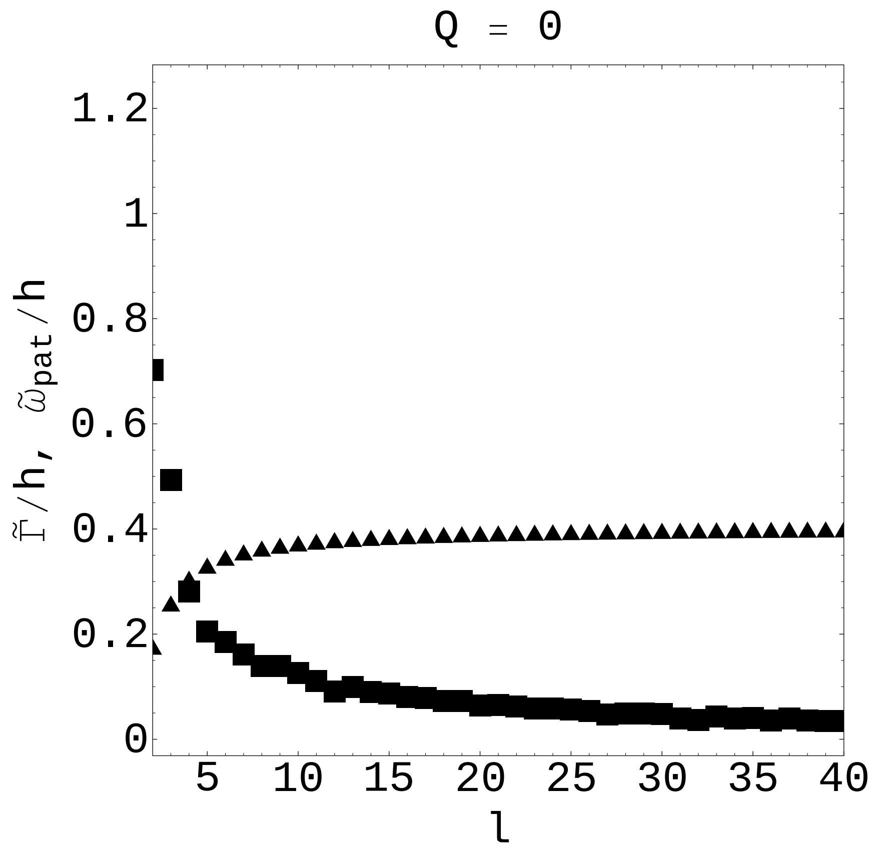
drawn: hollow, $Q = 0$; long dash: hollow, $Q = 0.5$;
short dash: with core $h_I = 0.2$, $Q_I = 0.1$, $Q = 0.5$;
dotted: with return (net zero) current

Unstable (electrostatic) diocotron surface modes: hollow beam Q=0

$\omega_{pattern} = \mathrm{Re}\,\omega/l,\ \Gamma = \mathrm{Im}\,\omega$

$k_{\parallel} = 0,\ \beta^{02}_{\alpha\phi} << 1,\ \omega^2_{p\alpha} << \Omega^2_{c\alpha}$





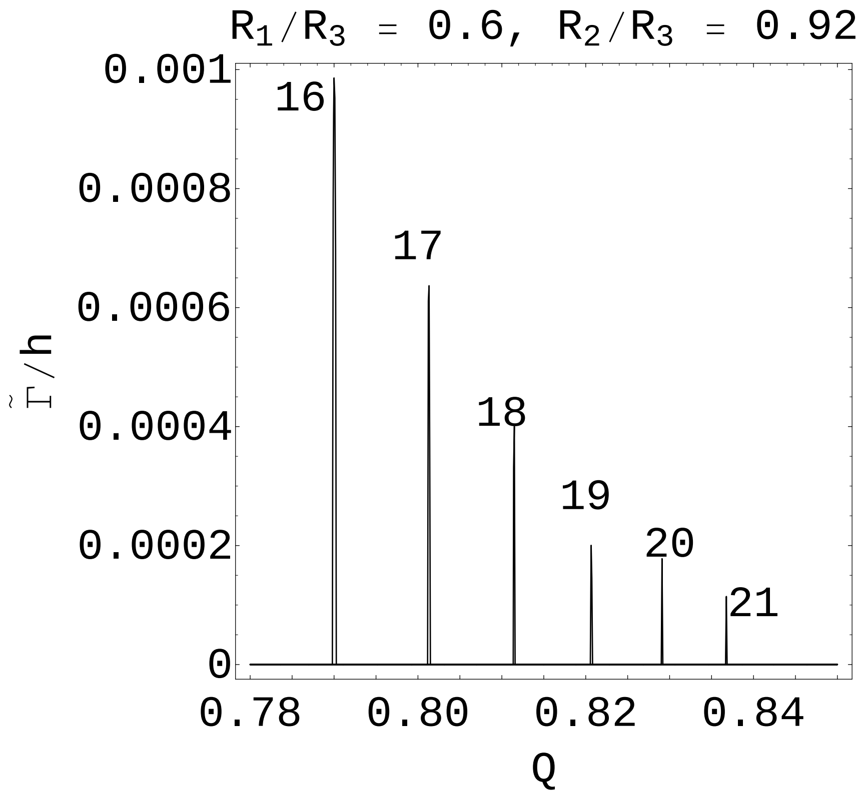
$$Q \equiv \frac{\beta_z^{02} f}{h}$$

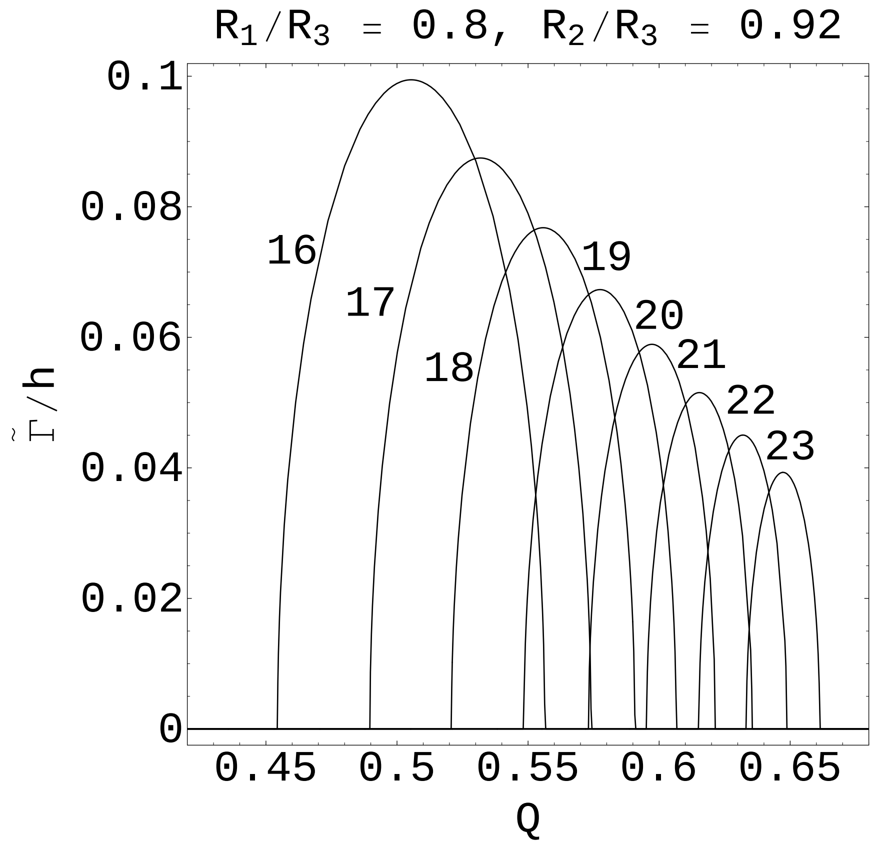
Applications: PSR 0943+10; PSR 0826-34

PSR	$\alpha(^\circ)$	$\beta(^\circ)$	P_1(s)	$P_3(P_1)$
B0943+10 (DR01)	11.58	–4.29	1.09	1.87
B0826–34 (Gupta et al. 2004)	$1-2$	1	1.848	0.50
B0826–34 (Esamdin et al. 2005)	0.5	–	1.848	$+6,-7$

l	$\tau_{\text{circ}}(P_1)$	$\tilde{\omega}_{\text{circ}}$
20	37	0.973
15	7.5	0.833
13	$+78,-91$	$0.99, 1.01$

Application: PSR0943+10; unstable modes





Application: PSR0943: $l = 20$, $\tilde{\omega}_{pat} = 0.973$

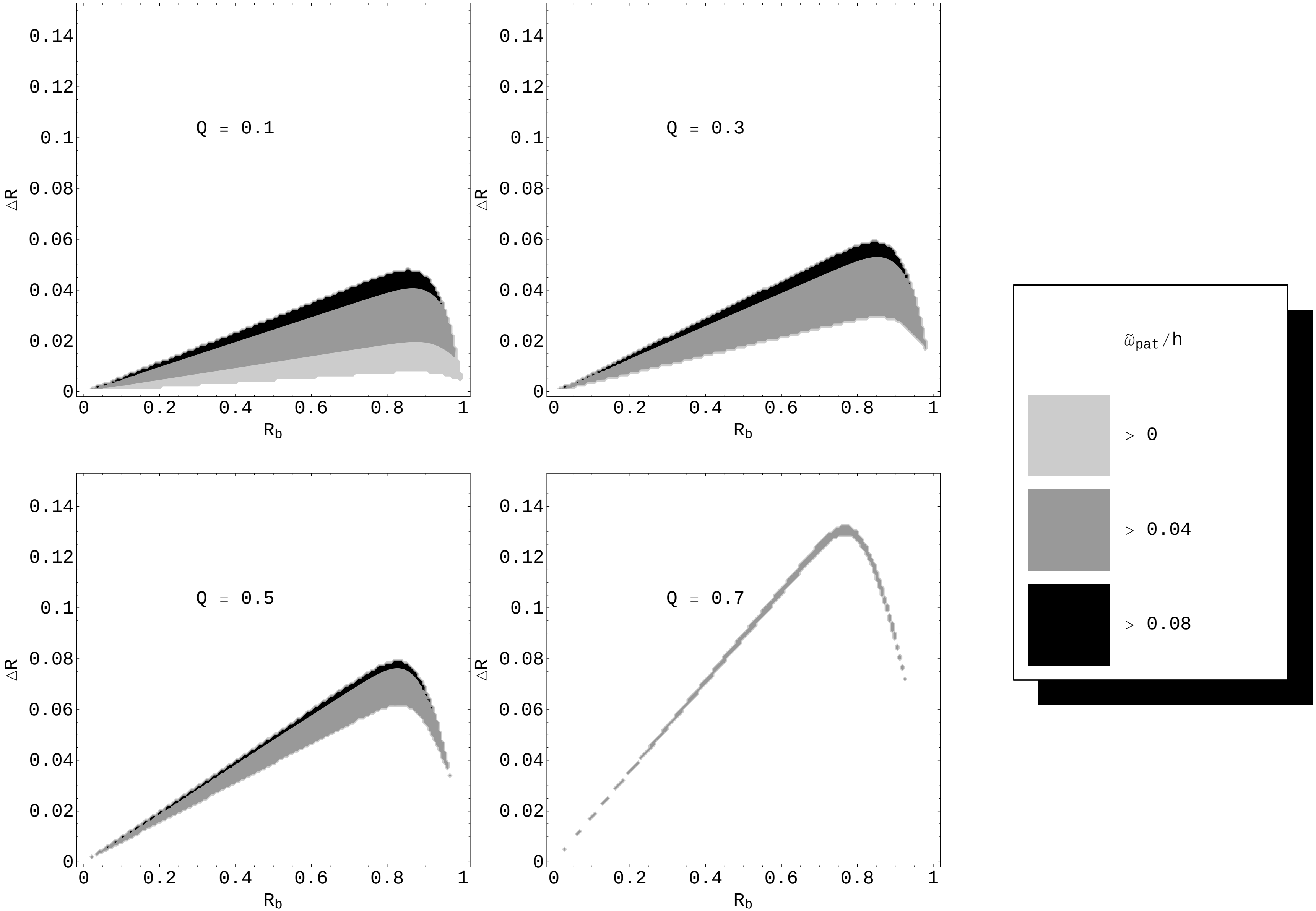
R_1/R_3	R_2/R_3	Q	$\tilde{\Gamma}$
0.65	0.92	0.80	1.8×10^{-2}
0.60	0.92	0.83	3.6×10^{-3}
0.80	0.92	0.60	1.14
0.65	0.86	0.77	7.2×10^{-2}
0.65	0.93	0.81	1.4×10^{-2}

$h = 19.5$, $f = 12$, $I(Q = 0.6) = 1.24 I_{GJ}$

Application: PSR0826: Domain of instability for $l = 13$

Two nested cones!: 4th degree eigen-value eqn.;

search Q-range for instability at $l = 13$



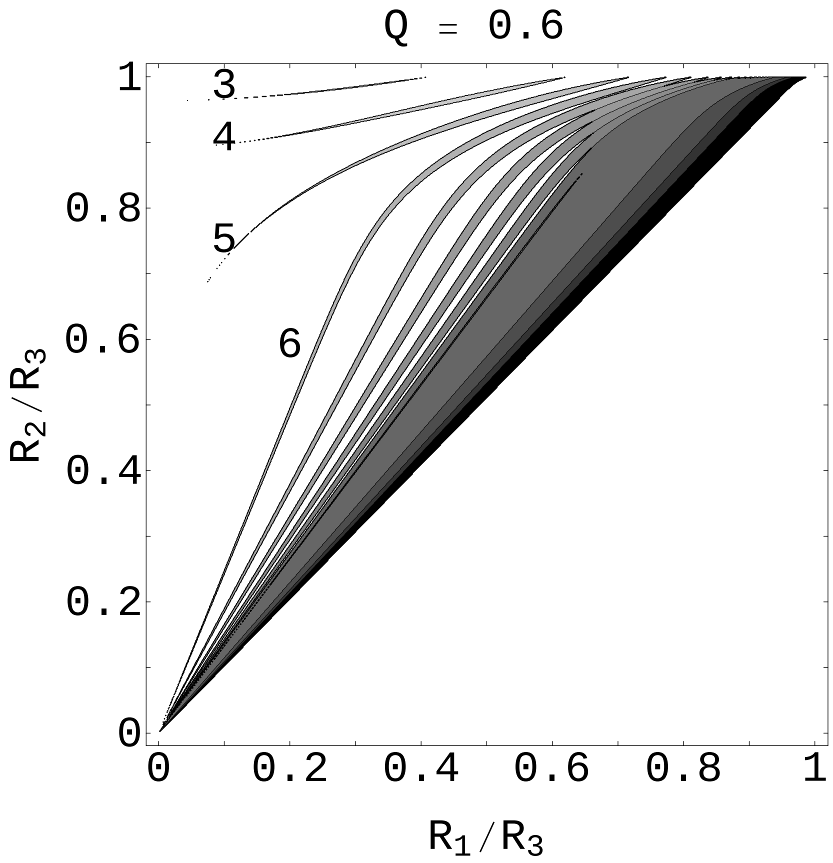
Conclusions

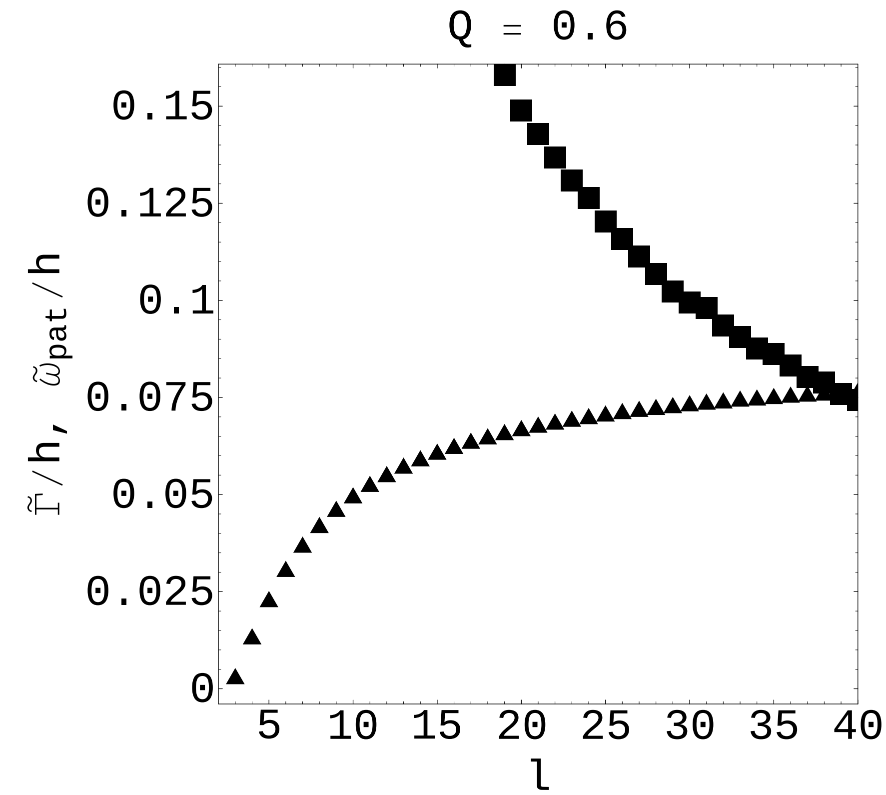
- Diocotron instability in out-flowing - non-neutral, differentially rotating - relativistic pair plasma for $k_{\|} = 0$;
- Charge-separated flow only has unstable $l \geq \gamma^2$;
- However for relativistic hollow $e^- - e^+$ beam: unstable $l < 40$;
- Identify l with number of sub-beams;
- pattern speed ω/l with carousel drift speed;
- Diocotron inst. allows for reversal of drift direction!
- Relativistic $e^- - e^+$ beam with GJ charge density does not corotate! super-GJ charge densities required
- Diagnostic for charge- and current density on open field lines.

Open questions

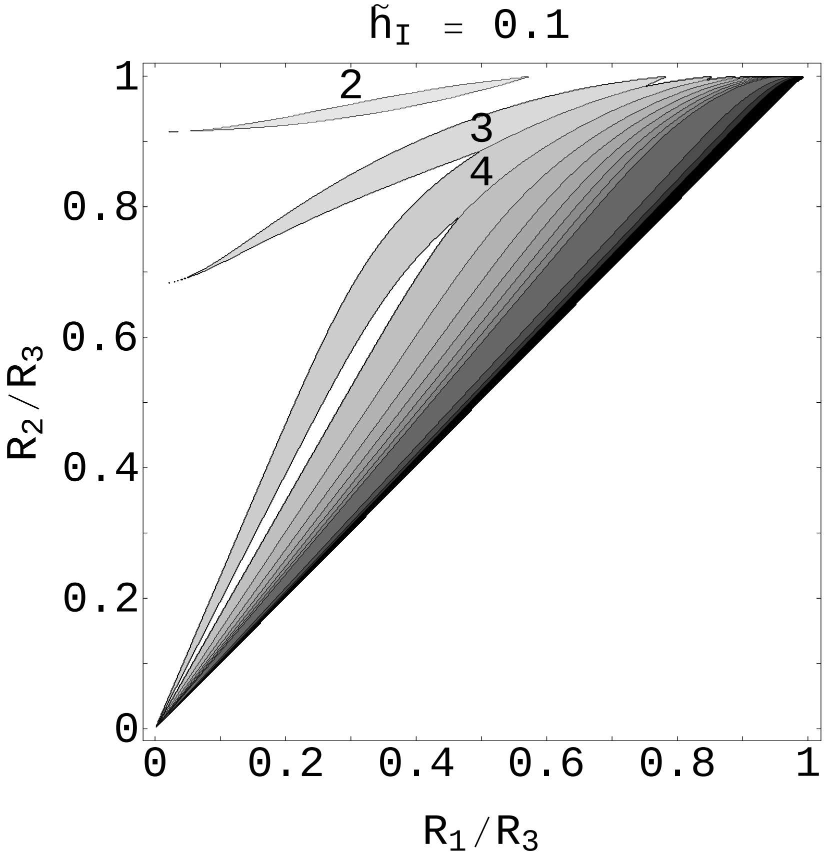
- Are there meta-stable geometries between which the electric circuit can switch, and the resulting emission pattern as well? (drift mode changing, nulling)
- Where is the ‘engine’?
- How do the particles know which field lines to select?
- How does a pulsar choose, and change its drift mode?
- How is the coupling between inner and outer gaps?
- Is there coupling between the magnetic poles?
- How do millisecond pulsars fit in; why are they neglected?!?
- If the diocotron instability is important to understanding drifting sub-pulses what is its non-linear evolution?

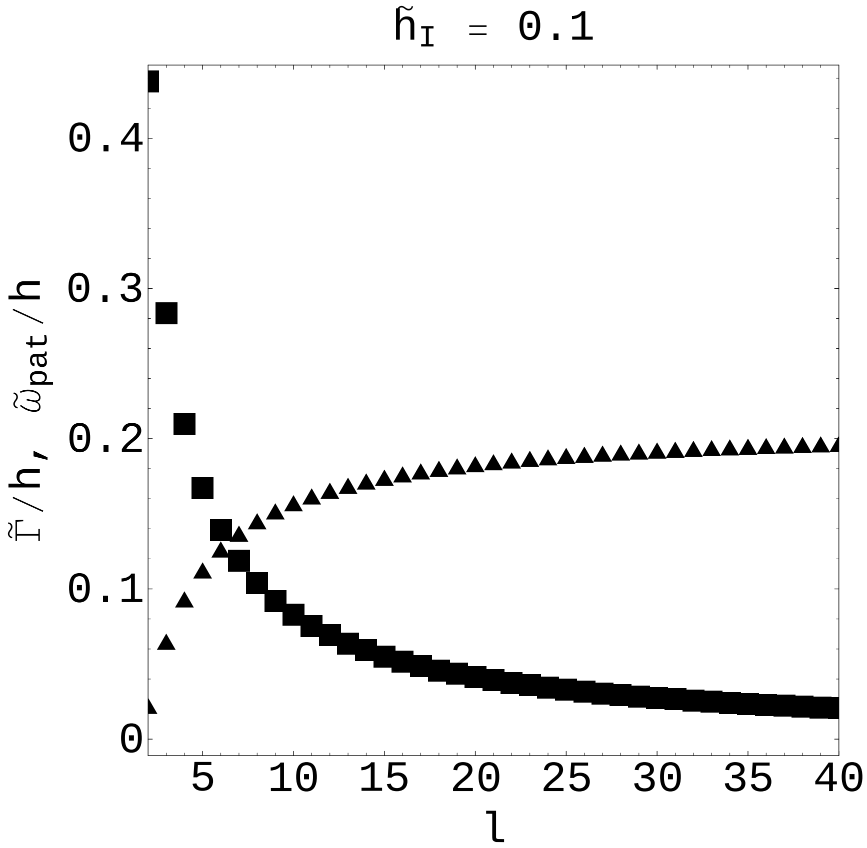
Unstable diocotron modes: hollow beam Q=0.8



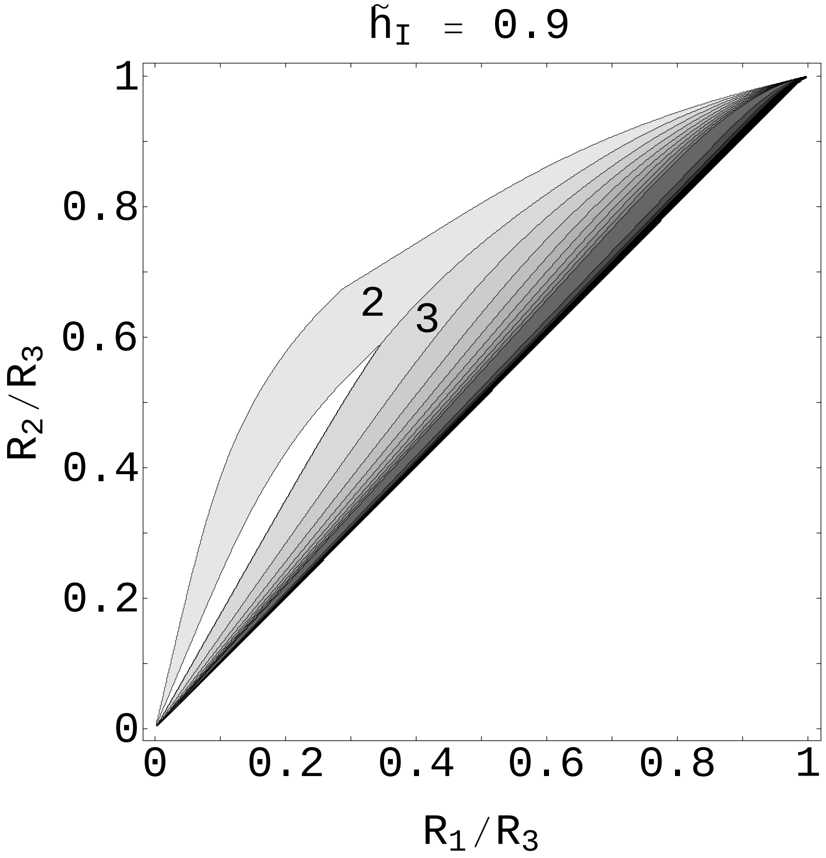


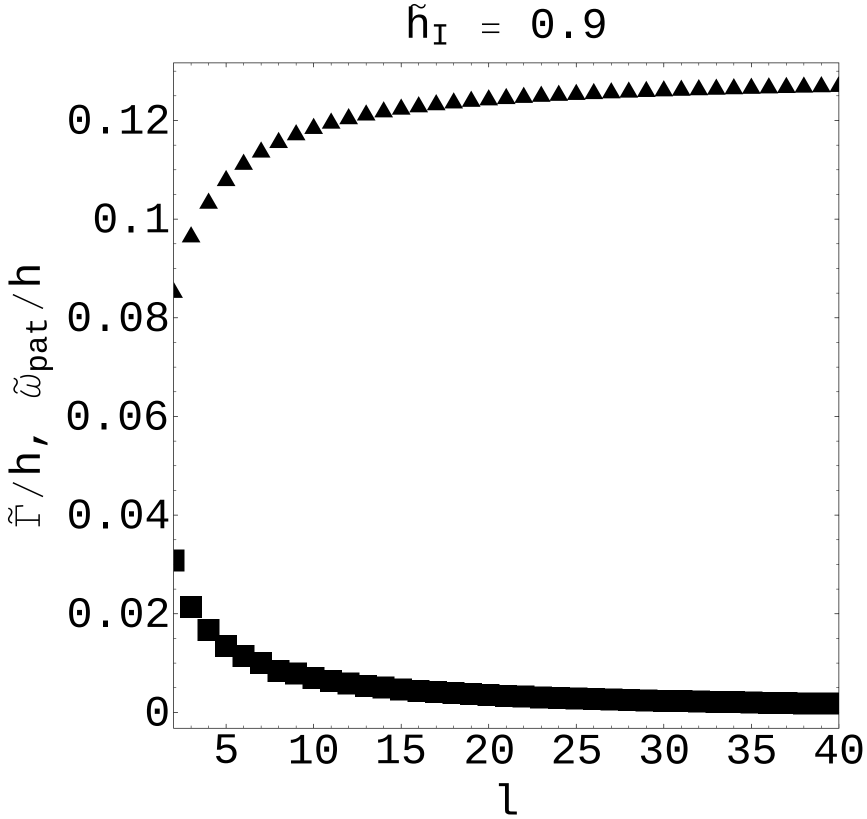
Unstable diocotron modes: charge-separated core: $h_1 = 0.1$



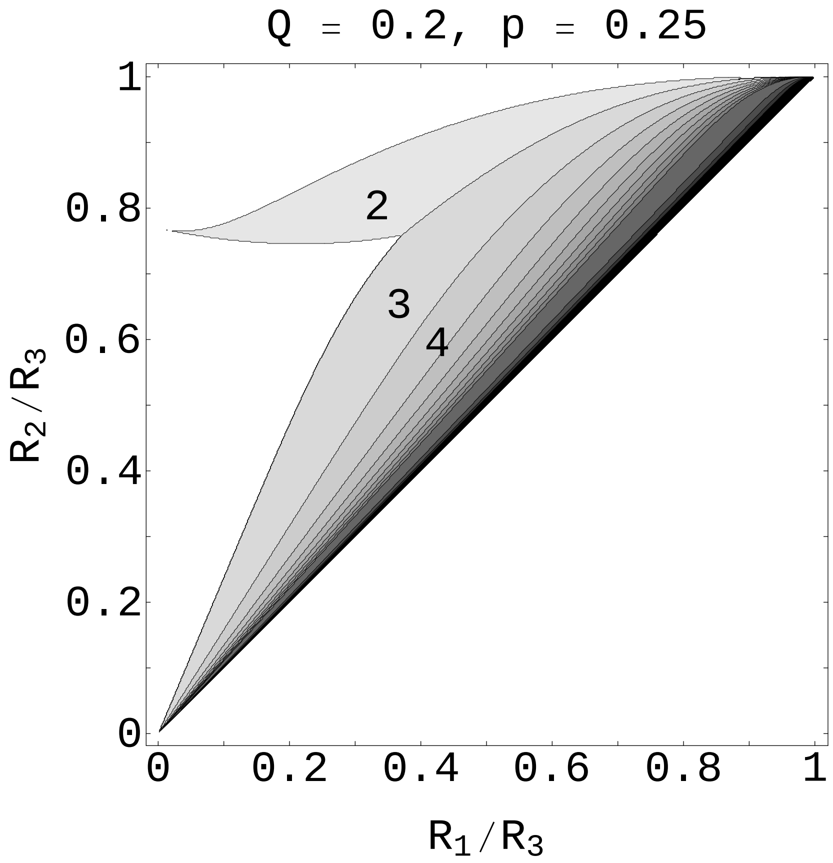


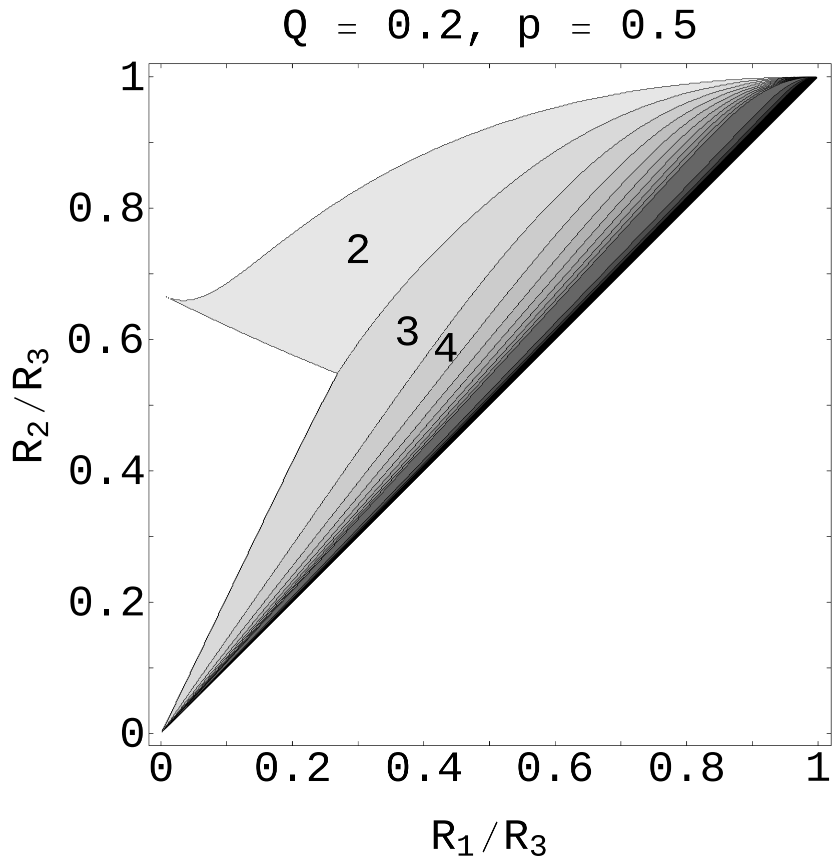
Unstable diocotron modes: charge-separated core: $h_1 = 0.9$



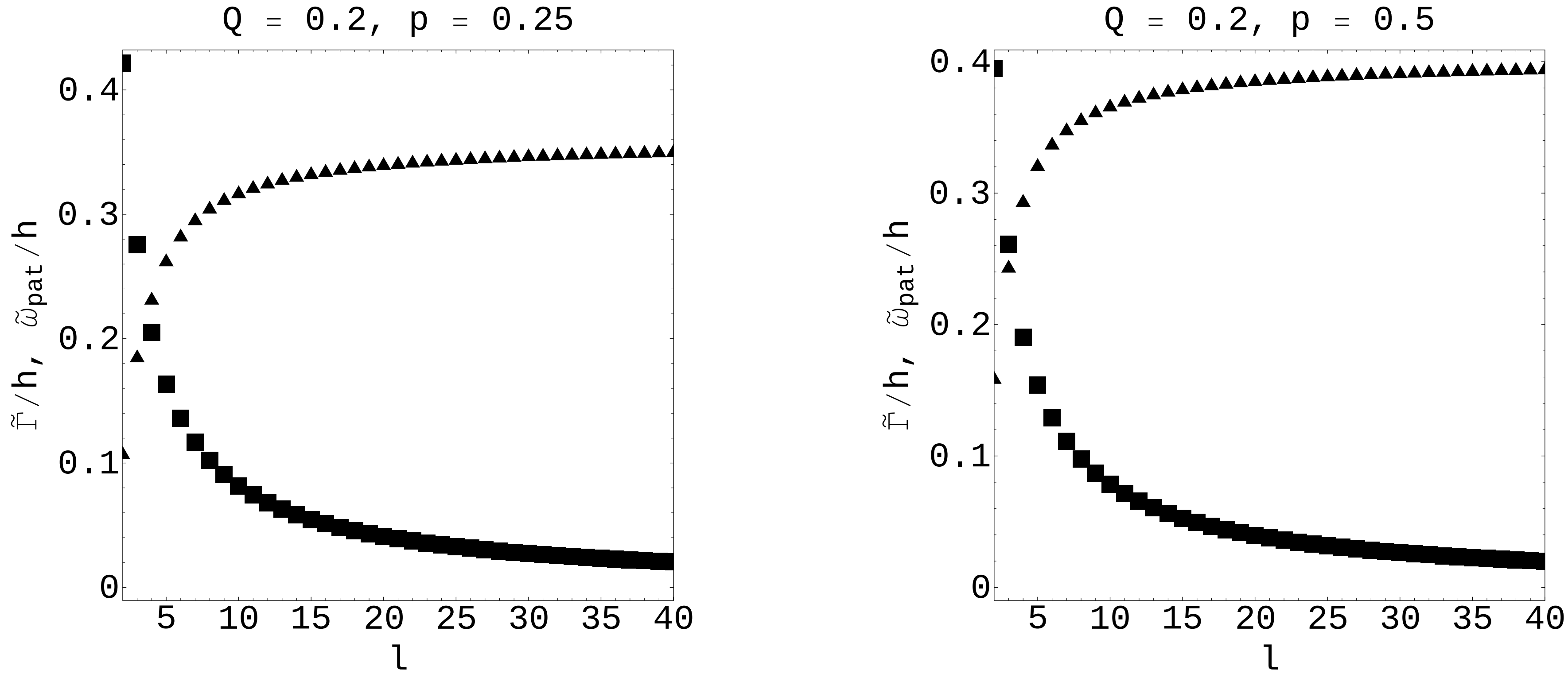


Unstable diocotron modes: incl. return current, $Q = 0.2$

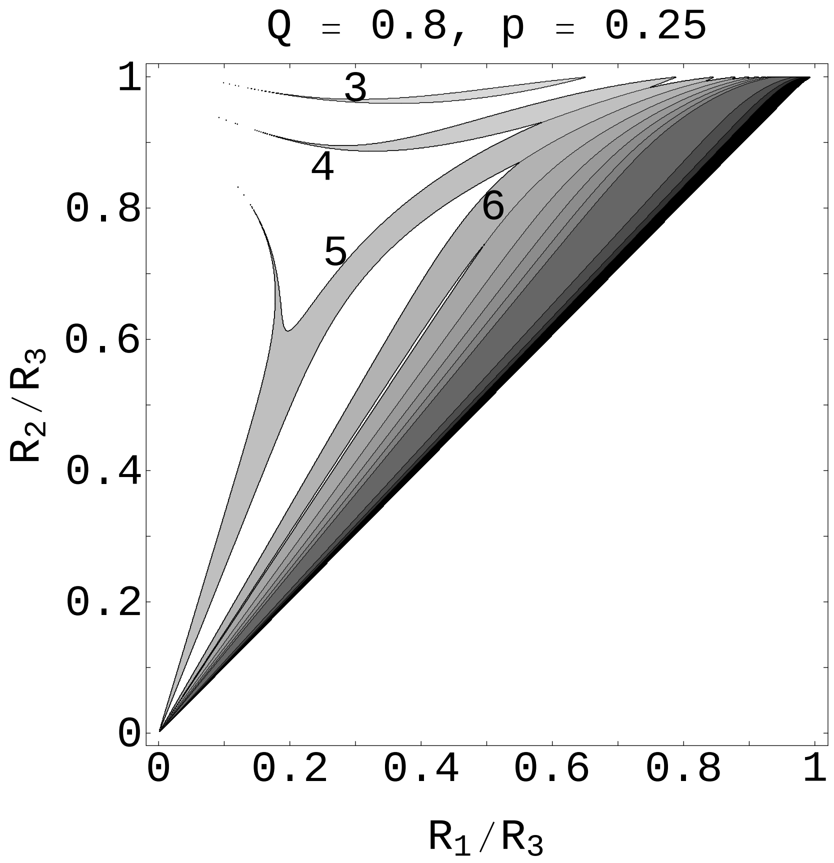


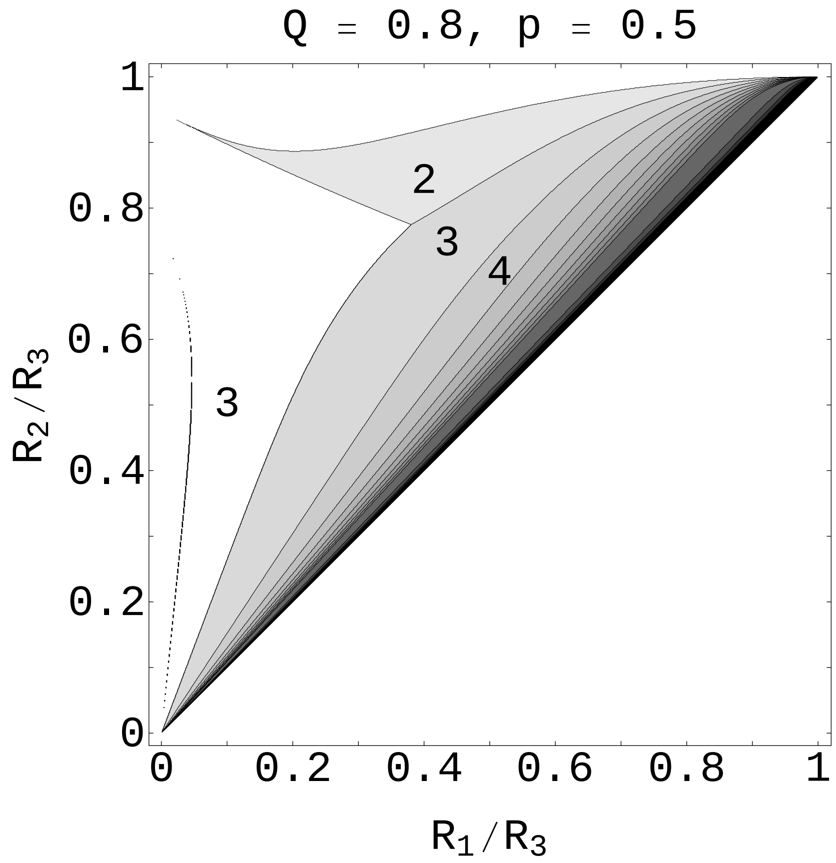


Unstable diocotron modes: incl. return current, $Q = 0.2$



Unstable diocotron modes: incl. return current, $Q = 0.8$





Unstable diocotron modes: incl. return current, $Q = 0.8$