Tori and their Destruction

- integrability ⇒ can write as action-angle form: $\left\{ \frac{d\underline{I}}{dt} = 0, \; \frac{d\underline{\theta}}{dt} = \underline{\omega}(\underline{I}) \right.$ const $\underline{I}$.

⇒ motion defines tori

$$\frac{d\theta}{dt} = \omega_1(I_1)\, t$$

$$\frac{d\phi}{dt} = \omega_2(I_2)\, t$$

scanning I_1, I_2 (linked to E)

⇒ define nested tori

etc.

e.g. box

$$\omega_1 = \pi^2 I_1 / ma^2$$

$$\omega_2 = \pi^2 I_2 / mb^2$$

$$E = I_1\omega_1 + I_2\omega_2$$

- motion on each toroidal surface will cover surface ergodically, unless $\frac{\omega_1}{\omega_2}$ rational.
- many surfaces ⇒ define volume of phase space.

- motion is conditionally periodic

i.e. ergodic motion on bounded surface
$\Rightarrow$ Poincaré recurrence guarantees nearby return to i.c.

$\Rightarrow$ How robust are toroidal surfaces?

i.e. if $H \to H_0(\underline{I}) + \epsilon H_1(\underline{I}, \underline{\theta})$

symmetry breaking perturbation

can we integrate the perturbed system to some order in ϵ?

i.e. transform $\underline{I}, \underline{\theta} \to \underline{J}, \underline{\phi}$

s/t $\left.\begin{aligned} \dot{\underline{J}} &= 0 \\ \dot{\underline{\phi}} &= \omega(\underline{J}) \end{aligned}\right\}$ to specified order in P.T.?

This is equivalent to exploring "fragility of surfaces" $\Rightarrow$ i.e. can nested structure be maintained with $O(\epsilon)$ deformation?

n.b. $\Rightarrow$ intro to canonical perturbation theory

→ start with 1 deg freedom:

$$J = I + O(\epsilon)$$
$$\phi = \theta + O(\epsilon)$$

then: old: I, θ

new: J, ϕ

o/t $\dot{J} = 0$ to $O(\epsilon)$

so have C.T. problem:

$p \Leftrightarrow I$ $\quad$ $P = J$
$q \Leftrightarrow \theta$ $\quad$ $Q = \phi$
(old) $\quad$ (new)

so

indep
$q \Leftrightarrow \theta$
$P \Leftrightarrow J$

dep
$p \Leftrightarrow I$
$Q = \phi$

$$p = \frac{\partial F}{\partial q} = \frac{\partial S}{\partial q}$$

$F = S$ here. $S =$ H-J fctn.

so

$I = \partial S / \partial \theta$

$\phi = \partial S / \partial J$

where: $S = S_0 + \epsilon \underbrace{S_1}_{\text{unknown}}$

$= J\theta + \epsilon S_1$

now here:

$S = S_0 + \epsilon S_1$

$\underbrace{H'(J)}_{\text{new, integrated Hamiltonian} \rightarrow \text{fctn of } J \text{ only}} \equiv \underbrace{K(J)}_{\text{re-label}}$

and can expand:

$$K(J) = K_0(J) + \epsilon K_1(J) + \ldots$$

$$K(J) = H(I, \theta)$$

$$= H_0\left(\frac{\partial S}{\partial \theta}, \theta\right) + \epsilon H_1\left(\frac{\partial S}{\partial \theta}, \theta\right) + \ldots$$

n.b.: $S' = S_0 + \epsilon S_1$
$= J\theta + \epsilon S_1$

$$I = J + \epsilon \frac{\partial S_1}{\partial \theta} \Rightarrow J = I - \epsilon \frac{\partial S_1}{\partial \theta}$$

$$\phi = \theta + \epsilon \frac{\partial S_1}{\partial J} \qquad \phi = \theta + \epsilon \frac{\partial S_1}{\partial J}$$

now, plugging S into relation for $H' = K$, etc

$$K_0(J) + \epsilon K_1(J) + \epsilon^2 K_2(J)$$
$$= H_0\left(J + \epsilon \frac{\partial S_1}{\partial \theta} + \epsilon^3 \frac{\partial S_2}{\partial \theta} + \cdots\right)$$
$$+ \epsilon H_1\left(J_1 + \epsilon \frac{\partial S_1}{\partial \theta} + \cdots,\ \theta\right)$$

cranking expansion to $O(\epsilon^2)$:

$$K_0(J) + \epsilon K_1(J) + \epsilon^2 K_2(J) + \cdots =$$

$$H_0(J) + \epsilon \frac{\partial S_1}{\partial \theta} \frac{\partial H_0}{\partial J} + \epsilon^2 \frac{\partial S_2}{\partial \theta} \frac{\partial H_0}{\partial J}$$

$$+ \epsilon H_1(J, \theta) + \epsilon^2 \frac{\partial S_1}{\partial \theta} \frac{\partial H_1(J)}{\partial J}$$

$$+ 1/2\, \epsilon^2 \left(\frac{\partial S_1}{\partial \theta}\right)^2 \frac{\partial^2 H_0}{\partial J^2}$$

matching order-by-order:

$$H_0 = K_0$$

$$K_1(J) = \frac{\partial S_1}{\partial \theta} \frac{\partial H_0}{\partial J} + H_1(J, \theta)$$

$$K_2(J) = \frac{1}{2}\left(\frac{\partial S_1}{\partial \theta}\right)^2 \frac{\partial^2 H_0}{\partial J^2} + \frac{\partial S_2}{\partial \theta} \frac{\partial H_0}{\partial J}$$

$$+ \frac{\partial S_1}{\partial \theta} \frac{\partial H_1}{\partial J} + \underset{\text{if present.}}{H_2}$$

etc.

For $O(\epsilon)$:

$$K_1(J) = \frac{\partial S_1}{\partial \theta}\frac{\partial H_0}{\partial J} + H_1(J,\theta)$$

$$= \underbrace{\frac{\partial S_1}{\partial \theta}\,\omega_0(J)}_{} + H_1(J,\theta)$$

winding frequency

where understand:

$$I = J + O(\epsilon)$$
$$\phi = \theta + O(\epsilon)$$

$$\boxed{\begin{aligned}\theta &= \phi - \epsilon\,\partial S_1/\partial J \\ I &= J + \epsilon\frac{\partial S_1}{\partial \theta}\end{aligned}}$$

Now, if define:

$$H_1 = \langle H_1\rangle + \tilde{H}_1$$

avg. — θ dep piece (symmetry breaking)

$$\langle H_1\rangle = \int_0^{2\pi}\frac{d\theta}{2\pi}\,H_1$$

(mean part)

then

averaging $K_1(J)$ eqn $\Rightarrow$

$$\boxed{K_1(J) = \langle H_1 \rangle}$$

and for S_1, from solvability:

$$\omega_0(J)\frac{\partial S_1}{\partial \theta} = K_1(J) - H_1$$
$$= \cancel{K_1(J)} - \cancel{\langle H_1 \rangle} - \tilde{H}_1$$
$$= -\tilde{H}_1$$

$$\boxed{\omega_0(J)\frac{\partial S_1}{\partial \theta} = -\tilde{H}_1}$$

Now, from before, as motion closed and periodic:

$$\tilde{H}_1 = \sum_{n=1}^{\infty} H_n(J)\, e^{in\theta}$$

$$S_1 = \sum_{n=1}^{\infty} s_n\, e^{in\theta} \qquad S = J\theta + \epsilon S_1$$

$\Rightarrow$

$$\boxed{S_1 = -\sum_n \frac{H_n(J)}{in\,\omega_0(J)}\, e^{in\theta}}$$

so can finally write full solution to $O(\epsilon)$:

$$\boxed{\begin{aligned} \phi &= \theta + \epsilon \frac{\partial S_1}{\partial J}(J, \theta) \\ J &= I - \epsilon \frac{\partial S_1}{\partial \theta}(J, \theta) \\ \omega &= \omega_0(J) + \epsilon \frac{\partial}{\partial J} K_1(J) \end{aligned}}$$

where:

$$\boxed{\begin{aligned} K_1 &= \langle H_1 \rangle \\ S_1 &= \sum_n \frac{i H_n(J)}{n\,\omega_0(J)}\, e^{in\theta} \end{aligned}}$$

so, in 1 d-o-f, can define strategy of perturbative 'integration'.

BUT, if # d-o-f's > 1 :

$\theta \to \underline{\theta}$ (i.e. θ, ϕ toroidal angles)

$n\omega_0(J) \to \underline{n} \cdot \underline{\omega_0}(J)$

$$\left(\text{i.e. } \underline{n} \cdot \underline{\omega_0} = n\omega_1(J_1) + m\omega_2(J_2) \right.$$
$$\left. \text{where } E = J_1\omega_1 + J_2\omega_2 \right)$$

then if

$\underline{n} \cdot \underline{\omega_0}(\underline{J}) \to 0$, denominator vanishes and perturbation theory fails

$\Rightarrow$ $\boxed{\text{welcome to the "problem of small divisors"}}$

$\Rightarrow$ identifies resonant surfaces

i.e. special surfaces of nested torus

where pitch of perturbation n/m = pitch of winding $\frac{\omega_2}{\omega_1}$.

These seem (and are) most fragile surfaces!

These surfaces are "resonant surfaces"

Classic example:

- tokamak field lines $\quad m = n\,q(r)$

$$q(r) = m/n$$

$q(r)$ ↓ pitch of lines (note shear) $\qquad m/n$ ↓ pitch of perturbation

- wave particle $\quad v = \omega/k$

v ↓ particle velocity $\qquad \omega/k$ ↓ wave phase velocity

n.b. here time makes resonance
$\partial S/\partial t = H - H'$

① ⇒ in vicinity of resonant surfaces, perturbative integration fails

② since rationals are set of measure $\mu \to 0$ on whole #'s, resonant surfaces are in some sense 'special'.

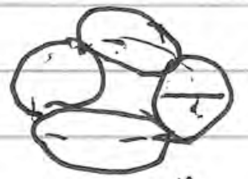
→ sneak preview

distortions called "islands" form

(const. H surface)

$I = 2$

$\longrightarrow$ + resonant perturbation $m = 4$, $n = 2$



filamentation occurs.

(const. H. surface)

$W_I \sim \sqrt{\delta B}$

upshot : – trajectory undertakes excursion from surface but remains near
– phase space structure resembles that of pendulum.

→ caveat : secular canonical perturbation theory works for 1 resonance, only.

strategy:

– remove resonance by transformation to frame co-rotating with resonant variables
Akin removal by frame change.
n.b. really avg. over fast variable

- limitation to removal of $\underline{\underline{1}}$ fast variable
  i.e. works as resonance $\Leftrightarrow$ slow

<u>Now</u>,

$$H = H_0(\underline{I}) + \epsilon H_1(\underline{I}, \underline{\theta})$$

if resonance: $r\omega_1 - s\omega_2 \cong 0$
$\Rightarrow$ resonance

$\omega_1 = \frac{d\theta_1}{dt}$ $\Rightarrow$ $\Theta = r\theta_1 - s\theta_2$ is "slow".

$\omega_2 = \frac{d\theta_2}{dt}$

<u>so</u>

$$(\underline{\omega} \cdot \nabla_{\underline{\theta}}) f(\theta) = (\omega_1 \partial_{\theta_1} + \omega_2 \partial_{\theta_2}) f$$
$$= (r\omega_1 - s\omega_2) f_{rs}$$
$$\sim O, \text{ near resonance.}$$

f dependence on Θ is h.O. $\rightarrow$ slow.

thus, before:

$$\underline{I},\ \underline{\theta} \rightarrow \underline{J},\ \underline{\phi}$$

now:

$$\left.\begin{matrix} I_1, & \theta_1 \\ I_2, & \theta_2 \end{matrix}\right\} \longrightarrow \left\{\begin{matrix} \overset{\text{slow}}{\overset{\downarrow}{r}}\,\theta_1 - s\,\theta_2, & \hat{J}_1 \\ \theta_2, & \hat{J}_2 \end{matrix}\right.$$

2 fast $\rightarrow$ 1 slow, 1 fast

$$F = S(\text{old positions, new momenta})$$
$$= S(\theta_1, \theta_2; \hat{J}_1, \hat{J}_2)$$

and type 2, so:

$$\boxed{S = \underbrace{(r\theta_1 - s\theta_2)\hat{J}_1 + \theta_2 \hat{J}_2}_{S_0} + \epsilon S_1}$$

so

$$I_1 = \partial S/\partial \theta_1 = r\hat{J}_1 + \epsilon\, \partial S_1/\partial \theta_1$$

$$I_2 = \partial S/\partial \theta_2 = (\hat{J}_2 - s\hat{J}_1) + \epsilon\, \partial S_1/\partial \theta_2$$

$$\phi_1 = \partial S/\partial \hat{J}_1 = r\theta_1 - s\theta_2 + \epsilon\, \partial S_1/\partial J_1$$

$$\phi_2 = \partial S/\partial \hat{J}_2 = \theta_2 + \epsilon\, \partial S_1/\partial J_2$$

$$H = H_0(\underline{I}) + \epsilon H_1(\underline{I}, \underline{\theta})$$

$$H_1 = \sum_{\ell, m} H_{\ell, m}(\underline{I})\, e^{i(\ell\theta_1 + m\theta_2)} \qquad \ell, m \neq 0$$

but know:

$$\phi_1 = r\theta_1 - s\theta_2 + \cancel{O}(\epsilon) \qquad \underline{\text{slow}}$$

$$\phi_2 = \theta_2 + \cancel{O}(\epsilon) \qquad \underline{\text{Fast}}$$

$\Rightarrow$

$$\theta_1 \cong (\phi_1 + s\phi_2)/r$$

$$\theta_2 \cong \phi_2$$

re-writing:

$$H_1 = \sum_{\ell,m} H_{\ell,m}(\hat{\underline{J}}) \exp\left[i \left(\frac{\ell}{r} \phi_1 + \frac{(\ell s + m r)}{r} \phi_2 \right) \right]$$

$\left.\begin{array}{l} \phi_2 \to \text{fast} \\ \phi_1 \to \text{slow} \end{array}\right\}$ distinction only possible near resonance where $r\omega_1 - s\omega_2 \to 0$

[Now, average out fast ϕ_2 dependence, and focus on evolution near resonance. ⇒ isolates region near resonance

Thus, will have

$$K_1 = K_1(\hat{\underline{J}}, \underset{\text{slow}}{\phi_1}) = \langle H_1 \rangle_{\phi_2}$$

$$\langle H_1 \rangle_{\phi_2} = \left\langle \sum_{\ell,m} H_{1\,\ell,m}(\hat{\underline{J}}) \exp\left[i \left(\frac{\ell}{r} \phi_1 + \frac{i}{r} (\ell s + m r) \phi_2 \right] \right\rangle_{\phi_2}$$

or,

Simply put:

$$\frac{\ell}{m} = \frac{-r}{s}$$ $\Rightarrow$ mode # pitch of perturbation must match pitch of resonance

so

$$\sum_{\ell, m} \rightarrow \sum_{p(-r/s)}$$ $\Rightarrow$ sum over all harmonics of perturbation resonant

$\therefore$

$$\sum_{\ell, m} \rightarrow \sum_{p} E_{pr, ps}$$

upon ϕ_2 integration: $\ell s = -mr$

$\frac{\ell}{m} = \frac{-r}{s}$ but $r\omega_1 - s\omega_2 \sim 0$

$\sim \frac{\omega_2}{\omega_1}$ $\Rightarrow \frac{\ell}{m}$ ratio set by resonance.

so $H_{1\,\ell, m} \rightarrow H_{1\,-m\frac{r}{s}, m}$ $\ell = \frac{-r}{s} m$

$\rightarrow H_{1\,-mr, ms}$

relabel

$\rightarrow H_{1\,-pr, ps}$

also $\frac{\ell}{r} = -\frac{m}{s}$ relabel: $-\frac{m}{s} \rightarrow -m$

$-m \rightarrow -p$

so $\langle\ \rangle_{\phi_2}$ perturbation is just harmonics of resonant pair $-r, s$.

$$\langle H_1 \rangle_{\phi_2} = \sum_{p=0}^{\infty} H_{1\,-rp,\,sp}\, e^{-ip\phi_1}$$

$\Rightarrow$

$$\boxed{\langle H \rangle = H_0(J) + \epsilon \sum_{p=0}^{\infty} H^{(1)}_{-pr,\,ps}\, e^{-ip\phi_1}}$$

From C-T rules:

$$\frac{\partial \langle H \rangle}{\partial \phi_2} = 0 \Rightarrow \frac{d}{dt}\hat{J}_2 = 0 \rightarrow$$ adiabatic invariant

and from C-T rules:

$$I_1 = r\hat{J}_1$$

$$I_2 = \hat{J}_2 - sJ_1$$

$\Rightarrow$ $\hat{J}_2 = I_2 + \frac{s}{r} I_1$ is adiabatic inv. of avgd Hamiltonian

ϕ_1 ~ res.

so $\frac{d\vec{J}_2}{dt} = 0 \Rightarrow \frac{d\phi_2}{dt} = \frac{\partial \langle H \rangle}{\partial \vec{J}_2} \equiv \omega(\vec{J}_2)$

Now, $\langle H \rangle = \langle H(\vec{J}_1, \phi_1, \vec{J}_2) \rangle$

→ For solution, need understand motion in $\vec{J}_1, \phi_1$

→ without loss of generality, simplify by:

$p = 0, \pm 1$ harmonics only, contribute

so

$$\langle H \rangle = H_0(\underline{\vec{J}}) + \epsilon H_{0,0}(\underline{\vec{J}}) + 2\epsilon H_{r,-s}(\vec{J}) \cos\phi_1$$

$H_{-r,s} = H_{r,-s}$

and seek motion near fixed points, as characterization

so, $\begin{array}{l} \dot{\hat{J}}_1 = 0 \\ \dot{\phi}_1 = 0 \end{array} \Rightarrow$ f.p. $\Leftrightarrow$ $\begin{array}{l} \partial\langle H \rangle / \partial\phi_1 = 0 \\ \partial\langle H \rangle / \partial\hat{J}_1 = 0 \end{array}$

these define: $\hat{J}_{1,0} = 0$, $\phi_{1,0} = 0$ $\Big\}$ fixed pts of motion

so

$$\frac{\partial \langle H \rangle}{\partial \phi} = 0 \Rightarrow -2\epsilon H^{(1)}_{r,-s} \sin\phi_1 = 0$$

$$\underbrace{\phi_1 = 0, \pm\pi}_{\text{fixed pts.}}$$

and

$$\frac{\partial \langle H \rangle}{\partial \hat{J}_1} = 0 \Rightarrow \frac{\partial H_0(\hat{J})}{\partial \hat{J}_1} + \epsilon \frac{\partial H_{0,0}(\hat{J})}{\partial \hat{J}_1}$$

$$+ 2\epsilon \frac{\partial H^{(1)}_{r,-s}}{\partial \hat{J}_1} \cos\phi_1 = 0$$

Now

$$\frac{\partial}{\partial J_1} = \frac{dI_1}{d\hat{J}_1}\frac{\partial}{\partial I_1} + \frac{\partial I_2}{\partial \hat{J}_1}\frac{\partial}{\partial I_2}$$

C-T rules $= r\dfrac{\partial}{\partial I_1} - s\dfrac{\partial}{\partial I_2}$

so, $\partial\langle H\rangle/\partial\hat{J}_1 = 0 \Rightarrow$ re-express

$$0 = \left(r\frac{\partial}{\partial I_1} - s\frac{\partial}{\partial I_2}\right) H_0(\underline{I})$$

$$+ \epsilon \frac{\partial}{\partial \hat{J}_1} H_{0,0} + 2\epsilon \frac{\partial H^{(1)}_{r,s}}{\partial \hat{J}_1} \cos\phi_1$$

$$= (r\omega_1 - s\omega_2) + \epsilon\left(\frac{\partial H^{(1)}_{0,0}}{\partial \hat{J}_1} + 2\frac{\partial H^{(1)}_{r,-s}}{\partial \hat{J}_1}\cos\phi_1\right)$$

0 on resonance!

so, to lowest order:

$\partial\langle H\rangle/\partial\hat{J}_1 = 0 \leftrightarrow d\phi_1/dt = 0$

is satisfied by <u>resonance condition</u>.

<u>so</u> $\hat{J}_{1,0}$ defined by resonance condition.

so fixed points:

$\hat{J}_{1,0} \Leftrightarrow$ resonant position
$r\,\omega_1(\underline{J}) - s\,\omega_2(\underline{J}) = 0$

$\phi_{1,0} \Leftrightarrow \sin\phi_1 = 0$

n.b.
see 22b

so $\langle H \rangle = \langle H(\hat{J}_1, \hat{J}_2, \phi_1) \rangle$

$$= \langle H(\underbrace{\hat{J}_{1,0}}_{\text{resonance}} + \underbrace{\delta\hat{J}_1}_{\text{excursion}}, \phi_1 \,|\, \underbrace{\hat{J}_2}_{\text{IOM}}) \rangle$$

so, expanding:

$$\langle H(\hat{J}_1, \phi_1) \rangle \cong H_0(\hat{J}_{1,0}) + \epsilon\left(H^{(1)}_{0,0}(\hat{J}_{1,0})\right)$$

$$+ \cancel{\left.\frac{\partial H_0}{\partial \hat{J}_1}\right|_{\hat{J}_{1,0}}}(\hat{J}_1 - J_{1,0}) + \frac{1}{2}\frac{\partial^2 H_0}{\partial \hat{J}_1^2}(\hat{J}_1 - J_{1,0})^2$$

reson.

$$+ 2\epsilon H^{(1)}_{r,-s}\cos\phi_1$$

$\Rightarrow$

$$\langle H(\hat{J}_1, \phi_1) \rangle \cong \cancel{\text{const.}} + \frac{1}{2}\frac{\partial^2 H_0}{\partial \hat{J}_1^2}(\hat{J}_1 - J_{1,0})^2 + 2\epsilon H^{(1)}_{r,-s}\cos\phi_1$$

so, have arrived at averaged Hamiltonian near resonance:

$$\boxed{\begin{aligned}\langle H(\hat{J}_1, \phi_1)\rangle &= \frac{1}{2}(\hat{J}_1 - \hat{J}_{1,0})^2 \left.\frac{\partial^2 H_0}{\partial \hat{J}_1^2}\right|_{\hat{J}_{1,0}} - F\cos\phi_1 \\ &\equiv \frac{G}{2}(\hat{J}_1 - \hat{J}_{1,0})^2 - F\cos\phi_1 \\ G &= \left.\frac{\partial^2 H_0}{\partial \hat{J}_1^2}\right|_{\hat{J}_{1,0}}, \quad F = 2\epsilon H^{(1)}_{\ell,s}\end{aligned}}$$

→ isomorphic to pendulum!

Recall for pendulum:

$$L = \frac{m\ell^2\dot{\theta}^2}{2} - mg\ell(1-\cos\theta)$$

$$H = p\dot{\theta} - L = \frac{p_\theta^2}{2m\ell^2} - mg\ell\cos\theta$$

$$\Rightarrow \quad H(\hat{J}_1, \phi_1) = \frac{G}{2}(J_1 - J_{1,0})^2 - F\cos\theta$$

is form of Hamiltonian near resonance

Note:

- assumes $\dfrac{\partial^2 H}{\partial \hat{J}_1^2} = \dfrac{\partial \omega}{\partial \hat{J}_1} \neq 0$ (NL/shear)

"accidental" resonance.

- for properties:

$$\langle H(\hat{J}_1, \phi)\rangle = \underbrace{\frac{G}{2}}_{\text{shear/NL parameter}}(\hat{J}_1 - \hat{J}_{1,0})^2 - \underbrace{F}_{\text{perturbation amplitude}}\cos\phi_1$$

and so:

$$\Delta\dot{J} = -F\sin\phi_1$$
$$\dot{\phi}_1 = G\,\Delta J$$

$$\phi_1 = 0 + \delta\phi$$
$$\Delta\ddot{J} + FG\,\Delta J = 0$$

near $\phi_1 = 0$

i.e.

$$\Delta \ddot{J}_1 = -F\cos\phi_{1,0}\, G\, \Delta J$$

$$\Delta \ddot{J}_1 + FG\cos\phi_{1,0}\, \Delta J = 0$$

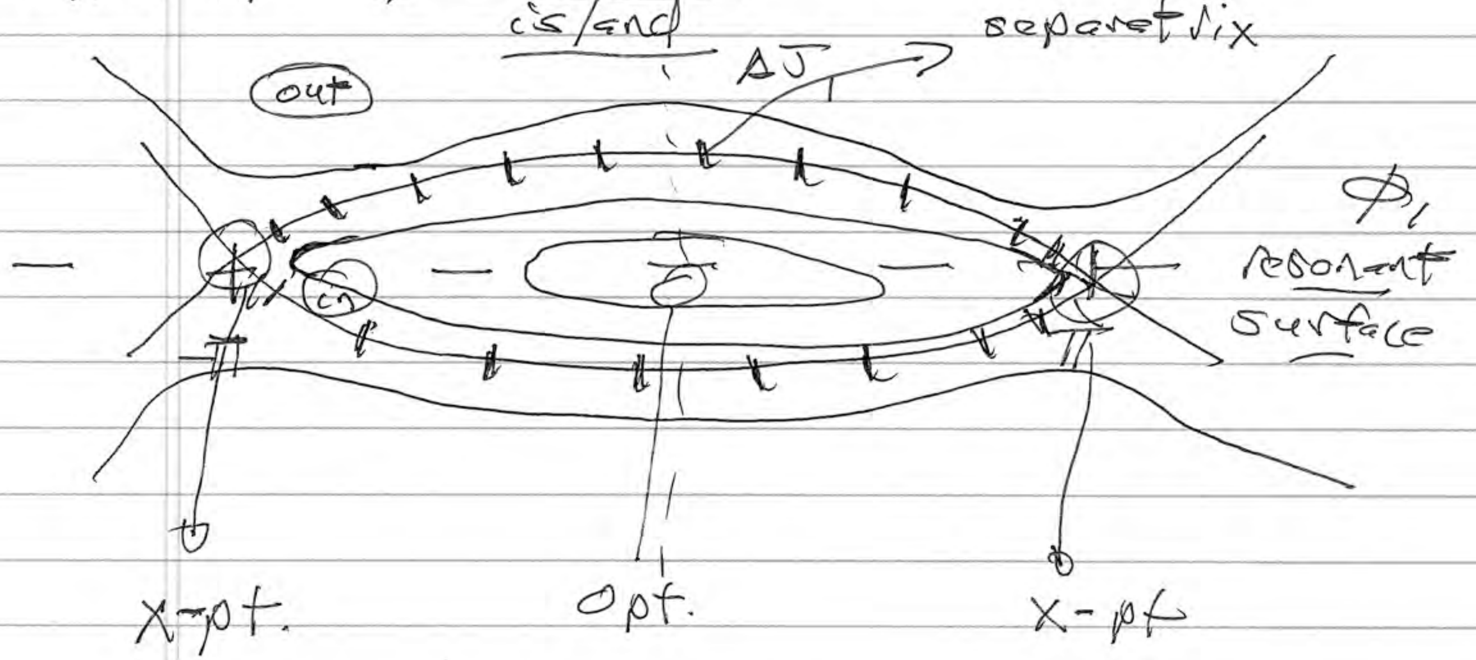
$FG > 0 \Rightarrow \phi_1 = 0$, stable fixed point

(o-pt / elliptic point)

$\phi_1 = \pm\pi$ $\Rightarrow$ unstable fixed pt.

(x-pt / hyperbolic pt.)

Contours: phase space island

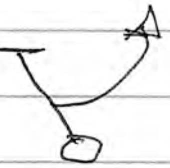


→ stable fixed pt. ↔ elliptic point ↔ O pt.
- island center
- center of trapped or libration region

→ unstable fixed point ↔ hyperbolic point ↔ X pt.
- island edge
- separatrix crossing point

→ separatrix 'separates' region of rotation (i.e. untrapped) from region of trapped (i.e. libration)


libration


rotation

→ libration: elliptic orbits
rotation: hyperbolic orbits

– width of separatrix – "island width"

$$(\Delta J)_{max} \cong 2(F/G)^{1/2}$$

$$\cong 2\left(-2G\,H^{(1)}_{r,-s} \Big/ \left.\frac{\partial^2 H_0}{\partial J_1^2}\right|_{\hat{J}_{1,0}}\right)^{1/2}$$

i.e. particle + wave:

$$H = (p + m\omega/k)^2/2m + q\phi_0 \cos kx$$

$$\Delta p = (q\phi_0 m)^{1/2}$$

$$\Delta v \cong (q\phi_0/m)^{1/2} \rightarrow \text{trapping width}$$

⇒ the <u>Big Picture</u>:

– resonant perturbations distort and foliate resonant tori in phase space, forming island chain structures.

i.e.

Note:

- structure localized to resonant surface
- $\left.\begin{array}{l}\text{trapped}\\ \text{untrapped}\end{array}\right\}$ orbits stay $\left\{\begin{array}{l}\text{trapped}\\ \text{untrapped.}\end{array}\right.$
- resonant surface is foliated but not destroyed.
- motion remains on surface, though surface is ruffled ...