Superintegrable Systems. I.

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Plan:

1. Superintegrable Hamiltonian systems

2. Examples

3. Quantum s. int. systems

3. Superintegrable systems on moduli spaces of G-flat connections on a surface

(based on joint work with S. Artamonov and J. Stokman)

Superintegrable systems

Degenerate integrability, noncommutative integrability; Fock, Pauli; Smorodinsky, Winterniz....
Nekhoroshev, Mischenko-Fomenko...

(M_{2n}, ω) - symplectic manifold $\{p_i, q^i\}$

$\omega = \sum_i dp_i \wedge dq^i$

$A = C^\infty(M_{2n})$, $H \in A$

Poisson bracket

$\{p_i, q^j\} = \delta_i^j$

$Z(H, A) = \{ a \in A \mid \{H, a\} = 0 \}$

centralizer of H in A

conserv. laws for the Ham. mech generated by H.

$(A, \{\cdot,\cdot\})$ Poisson algebra

Def. Hamiltonian flow generated by H is superintegrable if

(i) $\exists\ J \subset A$ of rank $2n-k$, i.e.
Poisson subalgebra

$\exists\ J_1, \dots, J_{2n-k} \in J$,

a maximal independent set

(ii) Poisson center of J (Poisson alg.)

$$Z(J) = \{ a \in J \mid \{a, b\} = 0,\ \forall b \in J \}$$

has rank k, i.e. contains maximum k independent functions $I_1, \dots, I_k$ and $H \in Z(J)$

$\boxed{\text{Liouville case } k = n}$ $J = I$

Thus algebraically a superintegrable system is

$$\underset{2n}{A} \supset \underset{2n-k}{J} \supset \underset{k}{I = Z(J)}$$

Poisson subalgebras

integrals of motion conserved quantities

Poisson commuting Hamiltonians

Geometrically

$$\begin{tikzcd}
\mathrm{Spec}(A) = M_{2n} \arrow[d, "p_1"] \\
\mathrm{Spec}(J) = \mathcal{P}_{2n-k} \arrow[d, "p_2"] \\
\mathrm{Spec}(I) = B_k
\end{tikzcd}$$

symplectic

generic k-dim isotropic fibers $\{\varphi_i\}$

$J_1 \dots J_{2n-k}$ local coord.

generic fibers are $(2n-2k)$-dim symplectic leaves

$I_1, .., I_k$ local coord. on B_k

$\underline{k<n}$

$k=n$ Liouville case

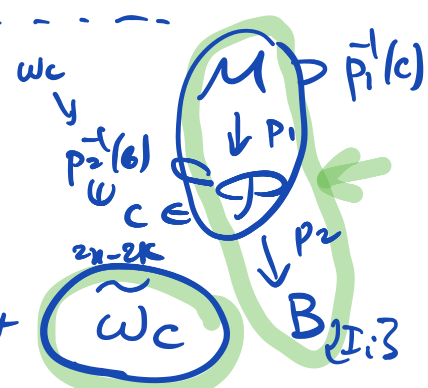
Theorem (Nekhoroshev)

- Flow lines of $I_1, \dots, I_k \in I$ generate

affine coordinates $\varphi_1, .., \varphi_k$ angle variables on level surfaces of $J_1 \dots J_{2n-k}$

(on $p_1^{-1}(c)$)

- In a nbd of $p_1^{-1}(c)$



$$\overset{2n}{\omega} = \sum_{i=1}^{k} \overset{2k}{dI_i \wedge d\varphi_i} + \overset{2n-2k}{\tilde{\omega}_c}$$

$\tilde{\omega}_c$ = sympl. form on $p_2^{-1}(p_2(c))$

- Each connected component of $p_1^{-1}(c)$ is $\simeq$ $\mathbb{R}^{\ell} \times T^{k-\ell}$
- Flow lines of any $H \in Z(J)$ are linear in $\varphi_1 .. \varphi_n$:

$$\varphi_i(t) = \omega_i(H,c)\,t + \varphi_i(0)$$

Refinement:

(k=n)

Liouville integrable on M_{2n}

n-dim invariant tori

$A_{2n} \supset J_n = I_n$

can be superintegrable

(k<n)

Superintegrable on M_{2n}

k-dim invariant tori

$A_{2n} \supset J_{2n-k} \supset I_k$

can be integrable

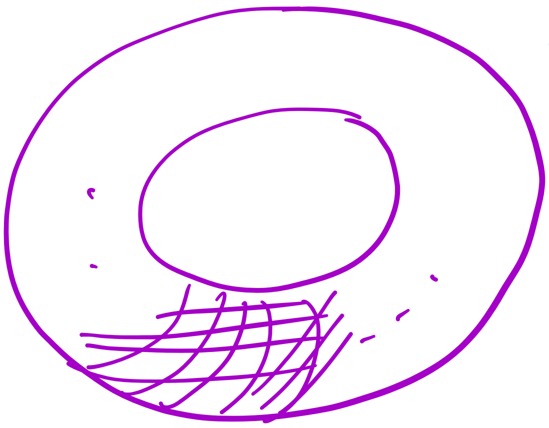
I_n Poisson commut. but central subalgebra

Refinement: $A_{2n} \supset J_{2n-k} \supset J_n \supset I_k$

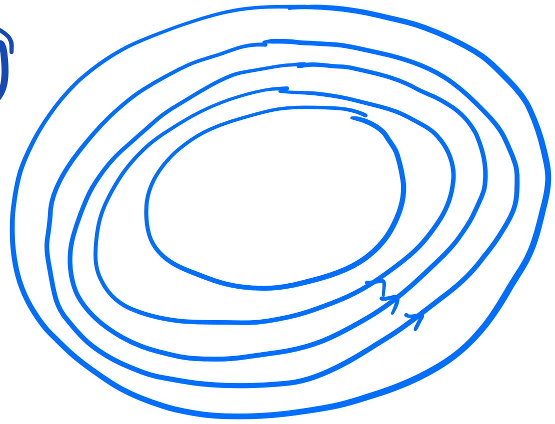
do not Poisson commute

$Z(J)$

M_4



I_1, I_2



J_1, J_2, J_3

2-dim torus densely covered by flow lines of I_1, I_2

Integrable, possibly non periodic trajectories

2-dim torus covered by 1-dim tori, level curves of J_1, J_2, J_3 (flow lines of I_1)

Superintegrable, periodic trajectories

Refinement, when exists

Examples:

1) Kepler system, $M = \mathbb{R}^3_p \times \mathbb{R}^3_q = T^*\mathbb{R}^3$

$$\omega = \sum_{i=1}^{3} dp_i \wedge dq^i ,$$

$$\boxed{H = \frac{1}{2}\vec{p}^2 - \frac{\gamma}{|q|}} ,$$

Momenta:

$$\vec{M} = \vec{p} \times \vec{q} \quad ✓ \qquad 6$$

Lenz vector:

$$\vec{A} = \vec{p} \times \vec{M} + \gamma \frac{\vec{q}}{|\vec{q}|} ,$$

Poisson brackets:

$$\begin{cases} \{M_i, M_j\} = \varepsilon_{ijk} M_k , \ \{M_i, A_j\} = \varepsilon_{ijk} A_k , \\ \{A_i, A_j\} = -2H \varepsilon_{ijk} M_k , \quad \begin{matrix} H>0 \\ -2H<0 \end{matrix} \qquad 6+1=7 \\ \boxed{\{H, M_i\} = \{H, A_i\} = 0} \end{cases}$$

Relations:

$$(\vec{M}, \vec{A}) = 0 , \quad \vec{A}^2 = \gamma^2 - 2\vec{M}^2 \cdot H$$

$\mathcal{M}_6 \to J_5 \to B_1$

$$C(T^*\mathbb{R}^3) \supset J_5 \supset I$$

$p \quad q$

$⑥ \qquad ⑤ \qquad ① \quad I = \langle H \rangle$

$$J_5 = \langle M_i, A_i, H \rangle / \text{Relations}$$

$$\begin{cases} \text{Poisson subalgebra,} \\ I = Z(J_5) \end{cases}$$

Geometrically

$$\underset{\approx \mathbb{R}^6}{M_6} \xrightarrow{p_1} \mathcal{P}_5 \xrightarrow{p_2} B_1 \approx \mathbb{R}$$

possible values of H

maximally superintegrable

Fibers of p_2 $(p_2^{-1}(E))$: sympl. leaves of $\mathcal{P}_5$

$\mathcal{O} \cong S^2 \times S^2 \subset so(4)^*$ $\qquad T^*S^2 \subset E(3)^*$ $\qquad \mathcal{O} \subset so(3,1)^*$

$E<0 \qquad E=0 \qquad E>0 \qquad E$

hidden $so(3,1)$ symmetry

Liouville integrable system: A_z, M_z, H

Quantum superintegrable systems

1) (M, ω) - symplectic $\begin{matrix} M_{2n} \\ \downarrow \\ B_n \end{matrix}$ integrable system.

$A_h = C_h(M)$ quantization of $C(M)$

associative algebra quantizing $C(M)$

in a sense that "$A_h \to C(M)$" as $h \to 0$ as a commutative algebra

and

$$\{f, g\} = \lim_{\hbar \to 0} \frac{\hat{f}\hat{g} - \hat{g}\hat{f}}{\hbar}$$

Def. A maximal commutative subalgebra $I_h \subset A_h$ is a quantum integrable system quantizing $\begin{matrix} M_{2n} \\ \downarrow \\ B_n \end{matrix}$ if

- I_h is a deformation of $I = C(B_n)$
- In every irreducible representation of A_h, the joint spectrum of I_h

has finite multiplicities.

(quantum integrable systems of finite type. $\begin{cases} A_h = \mathrm{Diff}(Q_n), \ \underset{2n}{M} = T^*Q_n \\ I_h \subset A_h \ \ n \text{ comm. d. oper.} \end{cases}$)

2) (M, ω) - symplectic, $\underset{2n}{M} \to \underset{2n-k}{P} \to B_k$ (*)

is a superintegrable system.

Let A_h be a quantization of $C(M)$.

__Def.__ A quantization of the superintegrable system (*) is

$$A_h \supset \overset{\text{gen. of symmetry } J_1, \dots, J_{2n-k}}{J_h} \supset I_h = \{\hat{I}_1, .., \hat{I}_k\} \qquad \{\hat{J}_i, \hat{I}_j\} = 0$$

- I_h = commutative of rank k, deforming $I = C(B_k)$
- J_h = associative, quantizing $C(P_{2n-k})$
- $I_h = Z(J_h)$
- In every representation of A_h

joint eigensubspaces of I_h are isomorphic to finite sums of irreducible J_h- modules.

Hydrogen atom (quantum Kepler system):

A_h

$\mathrm{Diff}(\mathbb{R}^3)_{\mathbb{C}} \supset \hat{J}_\delta \supset \hat{I} = \mathbb{C}\hat{H}$

$Z(\hat{J}_\delta) = \hat{I}$

$\uparrow$ quantum algebra of observables

$\uparrow$ Subalgebra generated by $\hat{M}_a$, $\hat{A}_a$, $\hat{H}$ with relations

$\hat{H} = -\Delta - \frac{\gamma}{|q|}$,

7 generators

2 relations

$[\hat{M}_a, \hat{M}_b] = i\varepsilon_{abc}\hat{M}_c$, $[\hat{M}_a, \hat{A}_b] = i\varepsilon_{abc}\hat{A}_c$

$[\hat{M}_a, \hat{H}] = [\hat{A}_a, \hat{H}] = 0$, $+2$ relations

$$\mathrm{Spec}(\hat{H}) = \{\text{discrete}\} \sqcup \underline{\{E=0\}} \sqcup \{E>0\}$$

$L_2(\mathbb{R}^3)$

$E=0$

$$E_n = -\frac{C}{n^2\hbar^2}, \quad n=1,2,\dots$$

$$\mathrm{Eigenspace}(E_n) \simeq V_{n-1}\otimes V_{n-1}, \quad \dim(V_\ell) = \ell+1$$

n^2 – degenerate.

- $\hat{M}_a$ acts diagonally, the action is reducible

$$V_{n-1}\otimes V_{n-1} \simeq V_0 \oplus V_2 \oplus \cdots$$

orbitals

This is a symmetry (not complete) of $\hat{H}$.

- $\hat{J}_5$ acts irreducibly on $V_{n-1}\otimes V_{n-1}$

This is the true symmetry of $\hat{H}$.

As $\hbar \to 0$, $n \to \infty$, $n\hbar = n_c$ is fixed

$$\underbrace{\dim(\mathrm{Eigenspace}(E_n))}_{\text{"}n^2\text{"}} \propto \hbar^{-2} = \hbar^{-\frac{\dim(p_2^{-1}(E_{n_c}))}{2}}$$

$$\dim(p_2^{-1}(E)) = 4$$

geometric quantization