

UNIVERSIDAD DE LOS ANDES

Three body problem in the spherical geometry

by

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Declaration of Authorship

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Abstract

Faculty of Sciences
Department of Physics

Bachelor in Physics

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The Thesis Abstract is written here (and usually kept to just this page). The page is kept centered vertically so can expand into the blank space above the title too...

Acknowledgements

The acknowledgements and the people to thank go here, don't forget to include your project advisor...

Contents

Declaration of Authorship	i
Abstract	iii
Acknowledgements	iv
List of Figures	vi
List of Tables	vii
Abbreviations	viii
Physical Constants	ix
Symbols	x
1 Introduction	1
1.1 Motivation	1
1.2 State of the art	1
2 The three body problem in the plane	2
2.1 The definition of the problem	2
2.2 The canonical transformation of the guiding centres	3
2.3 Integrability of the system	6
2.4 Analysis of the motion	8
3 The problem of a charged particle in the magnetic field of a monopole	9
3.1 Definition of the Lagrangian	9
3.2 The symmetries and its conserved quantities	10
3.3 Important quantities in the Hamiltonian formalism	14
A An Appendix	17

List of Figures

List of Tables

Abbreviations

LAH List Abbreviations **Here**

Physical Constants

Speed of Light $c = 2.997\,924\,58 \times 10^8 \text{ ms}^{-\text{s}}$ (exact)

Symbols

a	distance	m
P	power	W (Js^{-1})
ω	angular frequency	rads^{-1}

For/Dedicated to/To my...

Chapter 1

Introduction

1.1 Motivation

1.2 State of the art

Chapter 2

The three body problem in the plane

In this chapter a classic approach of a somehow general case of the three body problem in 2 dimensions is going to be presented. This will give some necessary intuition to develop the analogous problem in the spherical geometry. To begin with, the problem is going to be described in great detail; then its integrability is going to be proven; and finally, a formalism to describe the movement of the particles is going to be presented.

2.1 The definition of the problem

The three body problem presented here is that of three particles of electrical charge e and mass m confined to a plane, under the influence of a strong magnetic field perpendicular to it, and forces whose potentials satisfy translational and rotational symmetries in the plane.

Given this information, the Hamiltonian associated with this system has the form:

$$H = \sum_{i=1}^3 \frac{1}{2m} \left\| \vec{p}_i - e\vec{A}(\vec{q}_i) \right\|^2 + V(\vec{q}_1, \vec{q}_2, \vec{q}_3) + \frac{\omega_c^2}{2m} \sum_{i=1}^3 \|\vec{q}_i\|^2 \quad (2.1)$$

Where $\vec{q}_i = x_i\hat{i} + y_i\hat{j}$, $\vec{p}_i = p_{x_i}\hat{i} + p_{y_i}\hat{j}$ and $\vec{A}(\vec{q})$ is the magnetic vector potential, which satisfies $\nabla \times \vec{A} = B\hat{k}$.

Besides, the potential $V(\vec{q}_1, \vec{q}_2, \vec{q}_3)$ satisfies the symmetries:

$$V(R\vec{q}_1 + \vec{a}, R\vec{q}_2 + \vec{a}, R\vec{q}_3 + \vec{a}) = V(\vec{q}_1, \vec{q}_2, \vec{q}_3) \quad (2.2)$$

For any rotation R and translation \vec{a} in the plane.

2.2 The canonical transformation of the guiding centres

For the proof of integrability for this system, and for further analysis of the trajectories of the particles, let us perform the well known transformation of the guiding centres.

This transformation is defined by the following two equations:

$$\vec{\pi}_i = \vec{p}_i - e\vec{A}(\vec{q}_i) \quad (2.3)$$

$$\vec{R}_i = \vec{q}_i - \frac{\hat{k} \times \vec{\pi}_i}{eB} \quad (2.4)$$

The equation (2.3) passes from the canonical momentum \vec{p}_i to the linear momentum $\vec{\pi}_i$, which is much more intuitive and understandable; while the equation (2.4) transforms the general position \vec{q}_i to the position of the instantaneous guiding centre \vec{R}_i .

In a system without the interaction potentials, the electrically charged particles are known to perform the circular motion of the cyclotron with radii that depends on the initial linear momenta. In this case, the guiding centres would be constant in time as would be the linear momenta. However, with the introduction of an interacting potential, the momentum of each particle may vary making the guiding centre change too, which is why the instantaneous interpretation of the guiding centres is necessary.

Now, let us calculate the Poisson brackets for this new set of coordinates in a specific particle.

$$\begin{aligned}
\{\pi_1, \pi_2\} &= \frac{\partial \pi_1}{\partial q_\alpha} \frac{\partial \pi_2}{\partial p_\alpha} - \frac{\partial \pi_2}{\partial q_\alpha} \frac{\partial \pi_1}{\partial p_\alpha} \\
&= -e\delta_{\alpha 2} \frac{\partial A_1}{\partial q_\alpha} + e\delta_{\alpha 1} \frac{\partial A_2}{\partial q_\alpha} \\
&= -e \frac{\partial A_1}{\partial q_2} + e \frac{\partial A_2}{\partial q_1} \\
&= e(\nabla \times \vec{A})_3 = eB
\end{aligned}$$

$$\begin{aligned}
\{R_1, R_2\} &= \{q_1, q_2\} + \left\{q_1, -\frac{\pi_1}{eB}\right\} + \left\{\frac{\pi_2}{eB}, q_2\right\} + \left\{\frac{\pi_2}{eB}, -\frac{\pi_1}{eB}\right\} \\
&= \frac{1}{eB} \left(\cancel{\{p_1, q_1\}}^{-1} \cancel{e\{A_1, q_1\}}^0 + \cancel{\{p_2, q_2\}}^{-1} \cancel{e\{A_2, q_2\}}^0 \right) + \frac{eB}{(eB)^2} \\
&= \frac{-2}{eB} + \frac{1}{eB} = -(eB)^{-1}
\end{aligned}$$

$$\begin{aligned}
\{R_1, \pi_2\} &= \{q_1, \pi_2\} + \left\{\frac{\pi_2}{eB}, \pi_2\right\} \\
&= \cancel{\{q_1, p_2\}}^0 - \cancel{e\{q_1, A_2\}}^0 \\
&= \{R_2, \pi_1\} = 0
\end{aligned}$$

This Poisson brackets can be generalised to the transformation for the three particles. Taking $i, j = \{1, 2, 3\}$ and $\alpha, \beta = \{1, 2\}$:

$$\{\pi_{i,\alpha}, \pi_{j,\beta}\} = (eB) \delta_{ij} \epsilon_{\alpha\beta} \quad (2.5)$$

$$\{R_{i,\alpha}, R_{j,\beta}\} = -(eB)^{-1} \delta_{ij} \epsilon_{\alpha\beta} \quad (2.6)$$

$$\{R_{i,\alpha}, \pi_{j,\beta}\} = 0 \quad (2.7)$$

Equations (2.5)-(2.6) allow us to identify the proposed transformation as canonical. However, this is not the usual canonical transformation where the position coordinates and the momentum coordinates are canonical conjugates. In this special case, one component of the momentum is canonical conjugate with the other momentum coordinate, as equally happens for the position coordinates.

Now, with a huge magnetic field, if the potential of the interaction forces does not vary abruptly in space, we can use the approximation $\vec{R}_i \approx \vec{q}_i$ to average the potentials over the guiding centres, that is, we can replace \vec{q}_i for \vec{R}_i in $V(\vec{q}_1, \vec{q}_2, \vec{q}_3)$.

We can support the last approximation as follows: In the cyclotron problem, the radius of the circular motion described is proportional to the linear momentum and inversely proportional to the magnetic field. Then, in the presence of a big B , the radius of the cyclotron would shrink to a very small size. Regarding the case we are working with, the radii of the instantaneous cyclotron motion would be proportional to $\left\| (\hat{k} \times \vec{\pi}_i)(eB)^{-1} \right\|$ and its frequency to \sqrt{B} . As the potential V does not vary abruptly in the radii scale, the averaging of this motion over the guiding centres means that this potential does not sense that circular motion. Moreover, given the big frequency of the cyclotrons and the scale of variance of the potential, the scale of time of the local circular motions is far smaller than that of the motion of the guiding centres. Therefore, we can ignore the instantaneous quality of the circular motion, and take it as constant in a scale of time small enough for the motion of the guiding centres. In this sense we say that the coordinates for the guiding centres decouple from that of the linear momenta of the particles.

Before replacing the new set of coordinates in the Hamiltonian, it is necessary to do a scale transformation to obtain the proper Poisson brackets for the formal definition of canonical transformation, that is:

$$\begin{aligned}\vec{\pi}_i &\rightarrow (eB)^{-1/2} \vec{\pi}_i \\ \vec{R}_i &\rightarrow \sqrt{eB} \vec{R}_i\end{aligned}$$

With this consideration, the Hamiltonian of the system in the new set of rescaled coordinates is given by:

$$H = \sum_{i=1}^3 \frac{eB}{2m} \|\vec{\pi}_i\|^2 + V\left((eB)^{-1/2} \vec{R}_1, (eB)^{-1/2} \vec{R}_2, (eB)^{-1/2} \vec{R}_3\right) + \frac{\omega_c^2}{2meB} \sum_{i=1}^3 \left\| \vec{R}_i \right\|^2 \quad (2.8)$$

This Hamiltonian, given equation (2.7) can be decomposed in a Hamiltonian that describes the movement of the guiding centres, and other that describes the movement of the linear momenta. In one hand, the Hamiltonian for the linear momenta is easily identified with the harmonic oscillator, whereas the one that characterises the movement of

the guiding centres needs a deeper analysis.

2.3 Integrability of the system

As the Hamiltonian describing the trajectories of the linear momenta of the particles is that of an harmonic oscillator, this part of the problem is integrable and its solutions are widely known. The guiding centre Hamiltonian, in turn, needs to be analysed more deeply. For this purpose, let us take the following convention:

$$H_{gc} = \frac{\omega_c^{*2}}{2m} \sum_{i=1}^3 \|\bar{x}^2\| + \|\bar{y}^2\| + V^*(\bar{x}, \bar{y}) \quad (2.9)$$

Where $\bar{x} = (x_1, x_2, x_3)$ and $\bar{y} = (y_1, y_2, y_3)$, being x_i, y_i the rescaled coordinates of the guiding centres of the particles. For simplicity, the potential V and the constant ω_c have been rescaled to take into account the scale transform of the coordinates and maintain the original form of the Hamiltonian:

$$\omega^* = \frac{\omega}{\sqrt{eB}}$$

$$V^*(\bar{x}, \bar{y}) = V\left(\frac{\bar{x}}{\sqrt{eB}}, \frac{\bar{y}}{\sqrt{eB}}\right)$$

Clearly, the new potential V^* still has the symmetries expressed in the equation (2.2). Furthermore, in the new order for the scaled guiding centres coordinates, the Poisson brackets take the form:

$$\{y_i, x_j\} = \delta_{ij} \quad (2.10)$$

Now that the guiding centres Hamiltonian has been expressed in terms of the proper canonical set of coordinates, the fastest way to prove the integrability of the system is via the Liouville-Arnol'd theorem [?, Sect. 49]. For this theorem, it is only necessary to find 2 more independent integrals in involution (besides the Hamiltonian).

To get this 2 integrals, let us exploit the symmetries of the guiding centres Hamiltonian. We then define the generators of translations and rotation in the plane, which are symmetries of the potential:

$$\begin{aligned} T_x &= \sum_{i=1}^3 x_i \\ T_y &= \sum_{i=1}^3 y_i \end{aligned} \tag{2.11}$$

$$R_z = \frac{1}{2} \sum_{i=1}^3 (x_i^2 + y_i^2) \tag{2.12}$$

It is easily verifiable that these are indeed the symmetries generators. To see that, take the first order infinitesimal transformations of translation and rotation:

$$x_i \rightarrow x_i + \epsilon$$

$$y_i \rightarrow y_i + \epsilon$$

$$(x_i, y_i) \rightarrow (x_i + \epsilon y_i, y_i - \epsilon x_i)$$

Now note that for the infinitesimal translations, the potential of the primed coordinates is related to the potential of the normal coordinates by a directional derivative, which can be identified with the Poisson bracket of the potential V^* and each generator:

$$\begin{aligned} 0 &= V^*(\bar{x} + \epsilon, \bar{y}) - V^*(\bar{x}, \bar{y}) = \epsilon \sum_{i=1}^3 \frac{\partial V^*(\bar{x}, \bar{y})}{\partial x_i} = \epsilon \{V^*, T_x\} = 0 \\ 0 &= V^*(\bar{x}, \bar{y} + \epsilon) - V^*(\bar{x}, \bar{y}) = \epsilon \sum_{i=1}^3 \frac{\partial V^*(\bar{x}, \bar{y})}{\partial y_i} = \epsilon \{T_y, V^*\} = 0 \end{aligned}$$

For the infinitesimal rotation, the relation is analogous:

$$0 = V^*(\bar{x} + \epsilon \bar{y}, \bar{y} - \epsilon \bar{x}) - V^*(\bar{x}, \bar{y}) = \frac{\partial V^*(\bar{x}, \bar{y})}{\partial x_i} (\epsilon y_i) - \frac{\partial V^*(\bar{x}, \bar{y})}{\partial y_i} (\epsilon x_i) = \epsilon \{V^*, R_z\}$$

Therefore, we conclude that the generators of translations and rotations in the plane commute with the potential V^* due to its symmetries. Besides, the generator of rotations is multiple of the harmonic-like part of the guiding centres Hamiltonian which validates that R_z is other integral in involution. The generators of translations are not integrals in involution, for they do not commute with the harmonic potential, however, we can calculate a quantity in terms of these generators, which already commute with the potential V^* , to make it commute with the remaining part of H_{gc} :

$$L = T_x^2 + T_y^2 \quad (2.13)$$

This new quantity L clearly commutes with the potential V^* because the Poisson bracket is a linear differential operator in one component and it obeys the Leibniz rule. Moreover, it also commutes with the rotation generator R_z :

$$\begin{aligned} \{T_x^2 + T_y^2, R_z\} &= \sum_{i,j,k} \{x_i x_j + y_i y_j, x_k^2 + y_k^2\} \\ &= \sum_{i,j,k} \{x_i x_j, y_k^2\} + \{y_i y_j, x_k^2\} = \sum_{i,j,k} y_k \{x_i x_j, y_k\} + x_k \{y_i y_j, x_k\} \\ &= \sum_{i,j,k} y_k x_i \delta_{jk} + y_k x_j \delta_{ik} - x_k y_i \delta_{jk} - x_k y_j \delta_{ik} \\ &= \sum_{i,j} y_j x_i + y_i x_j - x_j y_i - x_i y_j = 0 \end{aligned}$$

As we found L as the last integral in involution, we conclude, by the Liouville-Arnol'd theorem, that the subsystem of guiding centres is integrable by quadratures.

2.4 Analysis of the motion

Chapter 3

The problem of a charged particle in the magnetic field of a monopole

With the objective to obtain some intuition about the N-body problem restricted to a spherical geometry, we study in this chapter the symmetries and trajectories of a charged particle under the influence of the magnetic field of a monopole. To achieve this we present the deduction, via the Lagrangian formalism, of the so called Poincaré cone [?] that characterises the trajectory of a particle in this situation. We then extrapolate the important symmetries used in the Lagrangian formalism to the Hamiltonian formalism to retrieve some important aspects of the classical counterparts of the known Haldane formalism [?].

3.1 Definition of the Lagrangian

Let L be the Lagrangian of a charged particle of charge $-e$ and mass m under the influence of a magnetic monopole of magnitude g . Then L takes the form:

$$L(\vec{x}, \dot{\vec{x}}) = \frac{m}{2} \|\dot{\vec{x}}\|^2 - e\vec{A}_{\hat{u}}(\vec{x}) \cdot \dot{\vec{x}} \quad (3.1)$$

Where $\vec{A}(\vec{x})$ is the vector potential of the magnetic monopole with singularity along the direction defined by the unit vector \hat{u} . It is known that there is no vector potential that is finite in \mathbb{R}^3 which reproduces the magnetic field of a monopole; in addition, the

different vector potentials identified by different unit vectors \hat{u} are related by a gauge transformation which leaves the trajectories invariant. This family of vector potentials are given by [?]:

$$\vec{A}_{\hat{u}}(\vec{x}) = \frac{g}{r} \frac{\hat{u} \times \hat{r}}{1 + \hat{u} \cdot \hat{r}} \quad (3.2)$$

3.2 The symmetries and its conserved quantities

The first thing to note in the previously defined Lagrangian is its time independence, which yields to the conservation of the Jacobi integral:

$$\frac{\partial L}{\partial \dot{\vec{x}}} \cdot \dot{\vec{x}} - L = m \left\| \dot{\vec{x}} \right\|^2 = m \left\| \dot{\vec{x}}_0 \right\|^2$$

With $\dot{\vec{x}}_0$ the initial velocity of the particle. Here the Jacobi integral clearly represents the kinetic energy of the particle, which is constant in time because the magnetic field does no work.

Now, due to the simplicity of the problem, one can suspect of many other symmetries. The next symmetry presented here is not associated with Lagrangian, but rather with the action invariance. If we define the action as in the equation 3.2, it can be seen that it may be invariant under a proper scale transform of position and time. It is not difficult to find this transform, and it is presented in equation 3.4.

$$S = \int_{t_1}^{t_2} L(\vec{x}, \dot{\vec{x}}) dt = \int_{t_1}^{t_2} \left(\frac{m}{2} \left\| \dot{\vec{x}} \right\|^2 - e \vec{A}_{\hat{u}}(\vec{x}) \cdot \dot{\vec{x}} \right) dt \quad (3.3)$$

$$\begin{aligned} \vec{x}' &= e^s \vec{x} \\ t' &= e^{2s} t \end{aligned} \quad (3.4)$$

As a result of this symmetry, by Noether's theorem there must be a conserved quantity implied. To calculate it we prefer the method stated in [? , Thm (dontforget)]; however, to apply this method, the Lagrangian must be parametrised to include the time t as a generalised coordinate. To achieve this, note that:

$$\dot{\vec{x}} = \frac{d\vec{x}}{dt} = \frac{\frac{d\vec{x}}{d\tau}}{\frac{dt}{d\tau}} := \frac{\overset{\circ}{\vec{x}}}{\overset{\circ}{t}}$$

Then the action can be written in terms of the new parameter τ :

$$S = \int_{t_1}^{t_2} L(\vec{x}, \dot{\vec{x}}) dt = \int_{\tau_1}^{\tau_2} \overset{\circ}{t} L(\vec{x}, \overset{\circ}{\vec{x}} \overset{\circ}{t}^{-1}) d\tau = \int_{\tau_1}^{\tau_2} L'(\vec{x}, \overset{\circ}{\vec{x}}, \overset{\circ}{t}) d\tau$$

Which by analogy with equation 3.2, gives the new parametrised Lagrangian L' :

$$L'(\vec{x}, \overset{\circ}{\vec{x}}, \overset{\circ}{t}) = \overset{\circ}{t} L(\vec{x}, \overset{\circ}{\vec{x}} \overset{\circ}{t}^{-1}) = \frac{m}{2\overset{\circ}{t}} \left\| \overset{\circ}{\vec{x}} \right\|^2 - e \vec{A}_{\vec{u}}(\vec{x}) \cdot \overset{\circ}{\vec{x}}$$

As we converted the symmetry of the action S in a symmetry of the Lagrangian L' , the invariance given by equation 3.4 becomes clear. Now, using [? , Thm (dontforget)], we obtain the conserved quantity in accordance with the transformation 3.4:

$$G = \left. \frac{\partial L'}{\partial \dot{q}_i} \frac{\partial q'_i}{\partial s} \right|_{s=0}$$

$$G = -m \left\| \frac{\overset{\circ}{\vec{x}}}{\overset{\circ}{t}} \right\|^2 t + \left(\frac{m \overset{\circ}{\vec{x}}}{\overset{\circ}{t}} - e \vec{A}_{\vec{u}} \right) \cdot \vec{x}$$

$$G = m \dot{\vec{x}}_0 \cdot \vec{x}_0 = -m \left\| \dot{\vec{x}}_0 \right\|^2 t + m \dot{\vec{x}} \cdot \vec{x}$$

Working the previous conserved quantity one can obtain an equation for the magnitude of the position in function of time:

$$2\dot{\vec{x}} \cdot \vec{x} = \frac{d\|\vec{x}\|^2}{dt} = 2 \left\| \dot{\vec{x}}_0 \right\|^2 t + 2\dot{\vec{x}}_0 \cdot \vec{x}_0$$

$$x^2 = x_0^2 + 2\dot{\vec{x}}_0 \cdot \vec{x}_0 t + \left\| \dot{\vec{x}}_0 \right\|^2 t^2 \quad (3.5)$$

From equation 3.5 it is important to note that the only way the radius of the particle stays constant is that the initial velocity of the particle is zero, otherwise, the time-quadratic term will always contribute to the increase of that radius. Furthermore, if the angular momentum of the particle $m\dot{\vec{x}}_0 \cdot \vec{x}_0$ is zero, we retrieve the trajectory of a particle in rectilinear motion. This means that the radial velocity of the particle is not affected by the magnetic field of the monopole, as expected from the symmetry of the field.

On the other hand, we note that once chosen a unit vector \hat{u} for the vector potential $\vec{A}_{\hat{u}}$, it is quite obvious that the original Lagrangian L in equation 3.1 is invariant under rotations around the unit vector \hat{u} , that is, under the following infinitesimal transformation:

$$\vec{x}' = \vec{x} + s(\hat{u} \times \vec{x}) \quad (3.6)$$

Then, as this transformation does not include the time t , we can perform the calculation of the conserved quantity over the original Lagrangian:

$$\begin{aligned} G_2 &= \left. \frac{\partial L}{\partial \dot{\vec{x}}} \cdot \frac{\partial \vec{x}}{\partial s} \right|_{s=0} \\ G_2 &= \left(m\dot{\vec{x}} - e\vec{A}_{\hat{u}} \right) \cdot (\hat{u} \times \vec{x}) \\ G_2 &= \left(m\vec{x} \times \dot{\vec{x}} \right) \cdot \hat{u} - eg \frac{\|\hat{u} \times \hat{x}\|^2}{(1 + \hat{x} \cdot \hat{u})} \\ G_2 &= \left(m\vec{x} \times \dot{\vec{x}} \right) \cdot \hat{u} - eg(1 - \hat{x} \cdot \hat{u}) \\ J_{\hat{u}} &:= \left(m\vec{x} \times \dot{\vec{x}} + eg\hat{x} \right) \cdot \hat{u} = ct \end{aligned}$$

Now, the last argument is valid for any unit vector \hat{u} chosen and this yields the conservation of the known as Poincaré vector in equation 3.7.

$$\vec{J} = \left(m\vec{x} \times \dot{\vec{x}} \right) + eg\hat{x} \quad (3.7)$$

This last symmetry is very meaningful because it restricts the trajectory of the particle to a cone centred in the origin with central vector \hat{J} . To verify this, it is only necessary to see that the radial component of the Poincaré vector is constant for all points in the trajectory, which means that the angle between \vec{J} and $\vec{x}(t)$ is a constant and that the path of the particle is restricted to a cone:

$$\vec{J} \cdot \hat{x} = eg$$

Furthermore, we can deduce from the conservation of the Poincaré vector that the angular momentum $\mathbb{L} = m\vec{x} \times \dot{\vec{x}}$ of the particle is constant in magnitude and that it determines the aperture of the cone of restriction:

$$\begin{aligned} \|\vec{J}\|^2 &= \|\mathbb{L}\|^2 + (gc)^2 \\ \|\mathbb{L}\| &= ct \\ \cos \theta &= \frac{\vec{J} \cdot \hat{x}}{\|\vec{J}\|} = \sqrt{\frac{(gc)^2}{\|\mathbb{L}\|^2 + (gc)^2}} \end{aligned} \tag{3.8}$$

From this equations it can be seen that the angle of aperture of the Poincaré cone is zero when the angular momentum \mathbb{L} cancel. Which means that the particle performs rectilinear motion, as deduced before from the other symmetries of the problem.

It is important to note here that if we restrict the trajectories of the particle to be in a sphere, we cannot carry a scale transform, hence we would not obtain the radius trajectory described in equation 3.5. However, a rotation is consistent with the norm conservation of the restriction to the sphere, and consequently we can obtain the Poincaré's vector invariance. The cone confinement of the particle together with the restriction of the trajectories to a constant radius would result in the particle describing a circular trajectory on the sphere.

Another important aspect that can be deduced from the set of equations 3.8 is that if we choose a magnetic monopole with big charge g compared with the angular momentum (in proper units), the angle of the Poincaré cone would tend to zero, which in the case of the particle restricted to the sphere, would mean that the radius of the circular motion would also tend to zero, in analogy with the already studied case of the particle in the plane. This gives us some clues as where to look for the analogue guiding center in the case of the magnetic monopole.

3.3 Important quantities in the Hamiltonian formalism

From the analysis carried out before, we can see some important quantities that are useful to describe the movement of particles in the presence of a magnetic monopole, some of which are associated with certain symmetries of the problem. Here we would like to study specially the angular momentum $\mathbb{L} = m\vec{x} \times \dot{\vec{x}}$ and the Poincaré vector $\vec{J} = (m\vec{x} \times \dot{\vec{x}}) + eg\hat{x}$. To do that, let us first calculate the Hamiltonian for the particle in the magnetic field of a monopole, this time restricting the problem to a sphere of radius R :

$$H(\vec{x}, \vec{p}) = \frac{1}{2m} \left\| \vec{p} + e\vec{A}_{\vec{u}}(\vec{x}) \right\|_{S^2}^2 \quad (3.9)$$

As the Hamiltonian is the Legendre transform of the Lagrangian, we obtain the generalised momentum \vec{p} in terms of the velocity of the particle. Moreover, we can see that the Hamiltonian is just the kinematic energy of the particle:

$$\vec{p} = \frac{\partial L}{\partial \dot{\vec{x}}} = m\dot{\vec{x}} - e\vec{A}_{\vec{u}} := \vec{\pi} - e\vec{A}_{\vec{u}}$$

$$H = \frac{1}{2m} \left\| \vec{\pi} \right\|_{S^2}^2$$

From here we can propose the angular momentum of the particle as $\mathbb{L} = \vec{x} \times \vec{\pi}$ and we can calculate its Poisson bracket. To do so, it is useful to calculate first some Poisson brackets related to the linear momentum $\vec{\pi} = \vec{p} + e\vec{A}$, as it was done in the first chapter:

$$\begin{aligned} \{\pi_i, \pi_j\} &= \frac{\partial \pi_i}{\partial x_l} \frac{\partial \pi_j}{\partial p_l} - \frac{\partial \pi_j}{\partial x_l} \frac{\partial \pi_i}{\partial p_l} \\ &= e\delta_{lj} \frac{\partial A_i}{\partial x_l} - e\delta_{li} \frac{\partial A_j}{\partial x_l} = e(\delta_{lj}\delta_{mi} - \delta_{li}\delta_{mj}) \frac{\partial A_m}{\partial x_l} \\ &= -e\epsilon_{ijk}\epsilon_{lmk} \frac{\partial A_m}{\partial x_l} \\ &= -e\epsilon_{ijk}(\nabla \times \vec{A})_k = e\epsilon_{ijk}B_k = -\frac{eg}{R^3}\epsilon_{ijk}x_k \end{aligned}$$

$$\{\pi_i, x_j\} = \frac{\partial \pi_i}{\partial x_l} \frac{\partial x_j}{\partial p_l} - \frac{\partial x_j}{\partial x_l} \frac{\partial \pi_i}{\partial p_l} = -\delta_{ij}$$

Then the algebra becomes a little bit easier for \mathbb{L}

$$\begin{aligned}
\{L_i, L_j\} &= \{\epsilon_{iab}x_a\pi_b, \epsilon_{jcd}x_c\pi_d\} = \epsilon_{iab}\epsilon_{jcd}\{x_a\pi_b, x_c\pi_d\} \\
&= \epsilon_{iab}\epsilon_{jcd}\left(x_ax_c\{\pi_b, \pi_d\} + \pi_bx_c\{x_a, \pi_d\} + x_a\pi_d\{\pi_b, x_c\} + \pi_b\pi_d\cancel{\{x_a, x_c\}}\right)^0 \\
&= \epsilon_{iab}\epsilon_{jcd}\left(-\frac{eg}{R^3}\epsilon_{bdk}x_ax_cx_k + \pi_bx_c\delta_{ad} - \pi_dx_a\delta_{bc}\right) \\
&= -\frac{eg}{R^3}\epsilon_{iab}(\delta_{jk}\delta_{cb} - \delta_{jb}\delta_{ck})x_ax_cx_k + (\delta_{bj}\delta_{ic} - \delta_{bc}\delta_{ij})\pi_bx_c - (\delta_{aj}\delta_{ib} - \delta_{ia}\delta_{jb})\pi_dx_a \\
&= -\frac{eg}{R^3}\left(x_j\cancel{\epsilon_{iab}x_ax_b}^0 - \epsilon_{aji}x_ax_bx_b\right) + (\delta_{ia}\delta_{jb} - \delta_{ib}\delta_{ja})x_a\pi_b \\
&= \epsilon_{ijk}(\epsilon_{abk}x_a\pi_b - eg\hat{x}_k) = \epsilon_{ijk}(L_k - eg\hat{x}_k)
\end{aligned}$$

Now, we can observe that \mathbb{L} does not follow the canonical relations for angular momentum, which is not surprising because the moment $\vec{\pi}$ used in the definition of \mathbb{L} is not the canonical momentum. We can fix this by taking a slight variation in \mathbb{L} :

$$\mathbb{J} := \mathbb{L} + eg\hat{x} \quad (3.10)$$

The Poisson bracket relation for this angular momentum is given by:

$$\begin{aligned}
\{J_i, J_j\} &= \left\{L_i + \frac{eg}{R}x_i, L_j + \frac{eg}{R}x_j\right\} \\
&= \{L_i, L_j\} + \frac{eg}{R}(\{L_i, x_j\} + \{x_i, L_j\}) + \left(\frac{eg}{R}\right)^2\cancel{\{x_i, x_j\}}^0 \\
&= \epsilon_{ijk}(L_k - eg\hat{x}_k) + \frac{eg}{R}\left(-\delta_{lj}\frac{\partial\epsilon_{iab}x_a(p_b + eA_b)}{\partial p_l} + \delta_{il}\frac{\partial\epsilon_{jcd}x_c(p_d + eA_d)}{\partial p_l}\right) \\
&= \epsilon_{ijk}(L_k - eg\hat{x}_k) + \frac{eg}{R}(-\epsilon_{jia}x_a + \epsilon_{ijc}x_c) \\
&= \epsilon_{ijk}(L_k + eg\hat{x}_k) = \epsilon_{ijk}J_k
\end{aligned}$$

Then we deduce that \mathbb{J} is a canonical angular momentum. It is not difficult to see that this is in fact the Poincaré vector in equation 3.7, and furthermore, that this is the canonical angular moment associated with the current canonical variables:

$$\begin{aligned}
\mathbb{J} &= \vec{x} \times \vec{\pi} + eg\hat{x} = m\vec{x} \times \dot{\vec{x}} + eg\hat{x} = \vec{J} \\
&= \vec{x} \times \vec{p} = \vec{x} \times \left(\vec{\pi} - e\vec{A}_{\hat{u}} \right) \\
&= \vec{x} \times \vec{\pi} - \vec{x} \times \left(\frac{g}{R^2} \frac{\hat{u} \times \vec{x}}{1 + \hat{u} \cdot \hat{x}} \right) \\
&= \vec{x} \times \vec{\pi} - \frac{g}{R^2} \left(\frac{R^2 \hat{u} - R\hat{x}(u)}{1 + \hat{u} \cdot \hat{x}} \right)
\end{aligned}$$

Appendix A

An Appendix