

# Trajectories Theory and Cosmogravity

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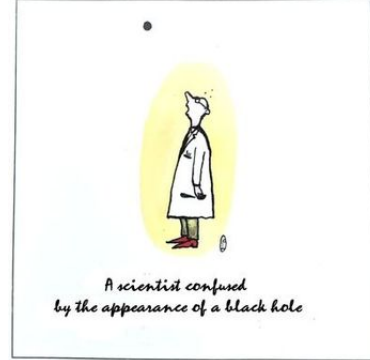
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## I - Schwarzschild Metrics

### I.1 External Metric

We wish to study the motion of a particle (massive or photon) in the external gravitational field of a centro-symmetric mass, without rotation, placed at the origin of spatial coordinates  $r, \theta, \varphi$  and time  $t$ . The model is a static space-time with spherical symmetry of metric :

$$ds^2 = -e^{\lambda(r)}dr^2 - r^2(d\theta^2 + \sin^2\theta d\varphi^2) + e^{\nu(r)}c^2dt^2$$

In **general relativity**, for a mass  $M$  without rotation, spherically symmetric, placed at the origin of the coordinates, in an empty space-time, the solution of Einstein's equations is :

$$\lambda + \nu = 0 \quad e^{\nu} = 1 - \frac{r_s}{r} \quad \text{with} \quad r_s = 2 \frac{GM}{c^2}$$

hence the expression of Schwarzschild's metric :

$$ds^2 = -\frac{dr^2}{1 - \frac{r_s}{r}} - r^2(d\theta^2 + \sin^2\theta d\varphi^2) + \left(1 - \frac{r_s}{r}\right) c^2 dt^2$$

$c$  the speed of light and  $G$  the gravitational constant .

$r_s$  is called « Schwarzschild rayon » or « black hole horizon ». It represents the limit of the region from which light and matter cannot escape.

This Schwarzschild solution is of remarkable importance since it is also the only solution to Einstein's equations outside of any spherically symmetric body of mass  $M$ , without rotation. This metric is therefore not limited to describe only black holes, it is also valid outside a star, planet, or any other spherically symmetric body without rotation. This result is known as the Birkhoff theorem (Gauss theorem in Newtonian gravitation).

The trajectories of a free particle are the geodesics of metric.

By reason of symmetry the trajectory is flat (we will take  $\theta = \frac{\pi}{2}$ ).

### I.1.1 Massive particle

The first integrals found using the Lagrangian  $\mathcal{L} = \frac{ds}{d\tau}$  are written :

$$(S_{pm}^e 1) \quad \frac{dt}{d\tau}(r) = \frac{E}{1 - \frac{r_s}{r}} \quad \text{and} \quad (S_{pm}^e 2) \quad \frac{d\varphi}{d\tau}(r) = \frac{cL}{r^2}$$

With two integration constants :  $E$  dimensionless and  $L$  one length. These functions reported in the expression  $ds = c d\tau$  involve :

$$(S_{pm}^e 3) \quad \left(\frac{dr}{d\tau}\right)^2 + V_{Spm}^e = c^2 E^2 \quad \text{where} \quad V_{Spm}^e(r) = c^2 \left(1 - \frac{r_s}{r}\right) \left(1 + \frac{L^2}{r^2}\right)$$

These relations verify the equations of the geodesics.

By deriving with respect to  $\tau$  the equation  $(S_{pm}^e 3)$  and for non-circular orbits, we deduce the following differential equation used to make the simulation :

$$(S_{pm}^e 4) \quad \frac{d^2 r}{d\tau^2} = -\frac{1}{2} \frac{dV_{Spm}^e}{dr} = \frac{c^2}{2r^4} (-r_s r^2 + 2rL^2 - 3r_s L^2) = f_{Spm}^e(r)$$

The study of the function  $V_{Spm}^e$  allows us to deduce that there can exist two circular orbits of radii :

$$\frac{L}{r_s} \left( L + \sqrt{L^2 - 3r_s^2} \right) \quad (stable) \quad \text{and} \quad \frac{L}{r_s} \left( L - \sqrt{L^2 - 3r_s^2} \right) \quad (unstable).$$

The equation  $S_{pm}^e 4$  is solved numerically by the Runge-Kutta method.

[Initial values III.6-A.2](#)

The observer who has stayed away from the black hole sees his colleague moving more and more slowly and eventually freezing when he reaches the  $r_s$  horizon. A traveler who falls into the black hole arrives at the center ( $r=0$ ) in a finite time while his colleague has the impression that he remains frozen on the horizon. (and, in practice, disappears because of the spectral shift).

### I.1.2 Photon

We keep the relations in  $t$  and  $\varphi$  with a different parameter  $\lambda$  of the proper time  $\tau$  since for a photon we have always  $d\tau = 0$ .

$$(S_{ph}^e 1) \quad \frac{dt}{d\lambda}(r) = \frac{E}{1 - \frac{r_s}{r}} \quad \text{and} \quad (S_{ph}^e 2) \quad \frac{d\varphi}{d\lambda}(r) = \frac{cL}{r^2}$$

These functions reported in the expression  $ds = 0$  involve :

$$(S_{ph}^e 3) \quad \left(\frac{dr}{d\lambda}\right)^2 + V_{Sph}^e = c^2 E^2 \quad \text{where} \quad V_{Sph}^e(r) = c^2 \left(1 - \frac{r_s}{r}\right) \frac{L^2}{r^2}$$

These relations verify the equations of the geodesics.

By deriving with respect to  $\lambda$  the equation  $(S_{ph}^e 3)$  and for non-circular orbits, we deduce the following differential equation used to make the simulation :

$$(S_{ph}^e 4) \quad \frac{d^2 r}{d\lambda^2} = -\frac{1}{2} \frac{dV_{Sph}^e}{dr} = \frac{c^2}{2r^4} (2rL^2 - 3r_s L_e^2) = f_{Sph}^e(r)$$

The study of the function  $V_{Sph}^e$  shows that there is an unstable circular orbit of radius  $\frac{3}{2}r_s$ .

The equation  $S_{ph}^e 4$  is solved numerically by the Runge-Kutta method.

[Initial values III.6-A.1](#)

## I.2 Internal Metric

We wish to study the motion of a particle (subject only to gravitation) inside a **constant density**, centro-symmetric, non-rotating object. The mass is placed at the origin of spatial coordinates  $r, \theta, \varphi$  and time  $t$ . The model is a static space-time with spherical symmetry. The solution of Einstein's equations gives the metric :

$$ds^2 = -\frac{dr^2}{\alpha(r)} - r^2(d\theta^2 + \sin^2\theta d\varphi^2) + \beta(r)^2 c^2 dt^2$$

where

$$\alpha(r) = 1 - \frac{r^2 r_s}{R^3}$$

$$\beta(r) = \frac{3}{2} \sqrt{1 - \frac{r_s}{R}} - \frac{1}{2} \sqrt{1 - \frac{r^2 r_s}{R^3}}$$

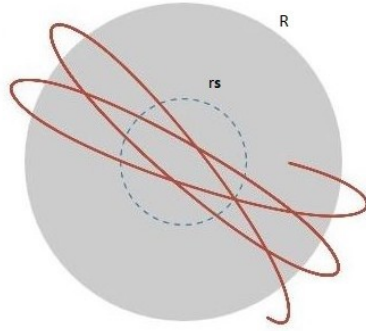
$R$  object radius

The trajectories of a free particle are the geodesics of metric.

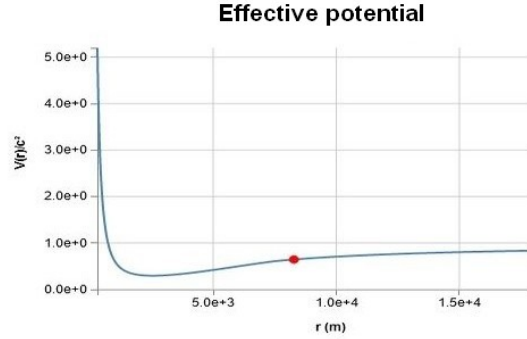
By reason of symmetry the trajectory is flat (we will take  $\theta = \frac{\pi}{2}$ ).

For the establishment of this metric see [Henri Andrillat - Introduction à l'étude des cosmologies](#) .

### I.2.1 Massive particle



$M=2e30$  kg  $r_0=5e3$  m  $R=7.5e3$  m  $U_{phi}(r_0)=4e7$  m/s  $U_r(r_0)=1.5e8$  m/s



The first integrals found using the Lagrangian  $\mathcal{L} = \frac{ds}{d\tau}$  are written :

$$(S_{pm}^i 1) \quad \beta(r)^2 \frac{dt}{d\tau}(r) = E \quad \text{and} \quad (S_{pm}^i 2) \quad \frac{d\varphi}{d\tau}(r) = \frac{c L}{r^2}$$

With two integration constants :  $E$  dimensionless and  $L$  one length. These functions reported in the expression  $ds = c d\tau$  involve :

$$(S_{pm}^i 3) \quad \left(\frac{dr}{d\tau}\right)^2 + V_{Spm}^i(r) = c^2 E^2 \quad \text{where} \quad V_{Spm}^i(r) = c^2 E^2 - c^2 \alpha(r) \left[ \frac{E^2}{\beta(r)^2} - \frac{L^2}{r^2} - 1 \right]$$

These relations verify the equations of the geodesics.

By deriving with respect to  $\tau$  the equation  $(S_{pm}^i 3)$  and for non-circular orbits, we deduce the following differential equation used to make the simulation :

$$(S_{pm}^i 4) \quad \frac{d^2 r}{d\tau^2} = -\frac{1}{2} \frac{dV_{Spm}^i}{dr} = -\frac{c^2 r r_s}{R^3} \left[ \frac{E^2}{\beta(r)^2} - \frac{L^2}{r^2} - 1 \right] + \frac{c^2 \alpha(r)}{2} \left[ \frac{-E^2 r r_s}{\beta(r)^3 \sqrt{\alpha(r)} R^3} + 2 \frac{L^2}{r^3} \right] = f_{Spm}^i(r)$$

The equation  $S_{pm}^i 4$  is solved numerically by the Runge-Kutta method.

[Initial values III.6-B.2](#)

### I.2.2 Photon

We keep relations in  $t$  and  $\varphi$  :

$$(S_{ph}^i 1) \quad \beta(r)^2 \frac{dt}{d\lambda}(r) = E \quad \text{and} \quad (S_{ph}^i 2) \quad \frac{d\varphi}{d\lambda}(r) = \frac{c L}{r^2}$$

These functions reported in the expression  $ds = 0$  involve :

$$\left(\frac{dr}{d\lambda}\right)^2 + V_{sph}^i(r) = c^2 E^2 \quad \text{and} \quad V_{sph}^i(r) = c^2 E^2 - c^2 \alpha(r) \left[ \frac{E^2}{\beta(r)^2} - \frac{L^2}{r^2} \right]$$

By deriving with respect to  $\lambda$  the equation  $(S_{ph}^i 3)$  and for non-circular orbits, we deduce the following differential equation used to make the simulation :

$$(S_{ph}^i 4) \quad \frac{d^2 r}{d\lambda^2} = -\frac{1}{2} \frac{dV_{sph}^i}{dr} = -\frac{c^2 r r_s}{R^3} \left[ \frac{E^2}{\beta(r)^2} - \frac{L^2}{r^2} \right] + \frac{c^2 \alpha(r)}{2} \left[ \frac{-E^2 r r_s}{\beta(r)^3 \sqrt{\alpha(r)} R^3} + 2 \frac{L^2}{r^3} \right] = f_{sph}^i(r)$$

The equation  $S_{ph}^i 4$  is solved numerically by the Runge-Kutta method.

[Initial values III.6-B.1](#)

## II - Kerr Metric

### II.1 General Theory

We wish to study the motion of a particle (massive or photon) in the gravitational field of a centro-symmetric, rotating mass, placed at the origin of the coordinates .

In **general relativity** , for a mass  $M$  in rotation, spherically symmetric, placed at the origin of the Boyer-Lindquist coordinates  $r, \theta, \varphi, t$ , in an empty space-time, the solution of Einstein's equations is the Kerr metric :

$$ds^2 = \frac{-\rho^2}{\Delta} dr^2 - \rho^2 d\theta^2 - (r^2 + a^2 + \frac{r_s r a^2}{\rho^2} \sin^2 \theta) \sin^2 \theta d\varphi^2 + \frac{2 r_s r a}{\rho^2} \sin^2 \theta c dt d\varphi + (1 - \frac{r_s r}{\rho^2}) c^2 dt^2$$

where  $\rho^2(r) = r^2 + a^2 \cos^2 \theta$   $\Delta(r) = r^2 - r_s r + a^2$   $a = \frac{J}{c M}$  (J angular momentum)

Unlike Schwarzschild metric, there is no equivalent of Birkhoff's theorem in Kerr metric. This geometry therefore only describes **rotating black holes**, not space-time external to other objects such as rotating stars or planets.

The trajectories of a free particle are the geodesics of the metric.

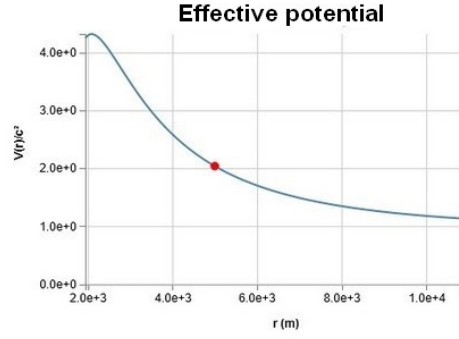
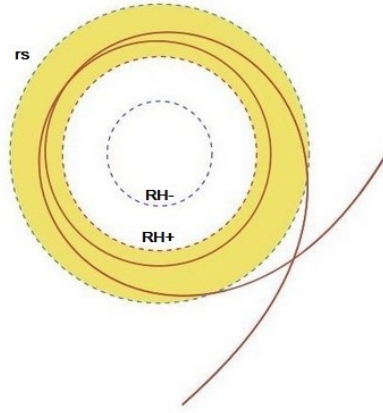
**Only flat trajectories will be studied** (with  $\theta = \frac{\pi}{2}$ ).

The event horizon corresponds to the change of sign of  $g_{rr}$  , i.e. to the solutions of the equation  $\Delta = 0$ . If  $a < \frac{r_s}{2}$  we get two values :

$$R_{H+} = \frac{r_s + \sqrt{r_s^2 - 4a^2}}{2} \quad \text{and} \quad R_{H-} = \frac{r_s - \sqrt{r_s^2 - 4a^2}}{2} \quad \text{so} \quad \Delta(r) = (r - R_{H+})(r - R_{H-})$$

The domain between  $r_s$  and  $R_{H+}$  is called ergoregion (in Schwarzschild metric there is no ergoregion  $a = 0$  and  $R_{H+} = r_s$ ) see [Éricourgoulhon - Relativité générale](#) .

## II.2 Massive particle



$$M=2e30\text{kg} \quad r_0=4.5e3 \text{ m} \quad a=1.418e3 \text{ m} \quad U_{\phi}(r_0)=7e8 \text{ m/s} \quad U_r(r_0)=-4.25e8 \text{ m/s}$$

The first integrals found using the Lagrangian  $\mathcal{L} = \frac{ds}{d\tau}$  are written :

$$(K_{pm1}) \quad \frac{dt}{d\tau}(r) = \frac{1}{\Delta(r)} \left[ (r^2 + a^2 + \frac{r_s}{r} a^2) E - \frac{r_s a}{r} L \right] \quad \text{and} \quad (K_{pm2}) \quad \frac{d\varphi}{d\tau}(r) = \frac{c}{\Delta(r)} \left[ \frac{r_s a}{r} E + (1 - \frac{r_s}{r}) L \right]$$

With two integration constants :  $E$  dimensionless and  $L$  one length.

These functions reported in the expression  $ds = c d\tau$  involve :

$$(K_{pm3}) \quad \left( \frac{dr}{d\tau} \right)^2 + V_{Kpm} = c^2 E^2 \quad \text{where} \quad V_{Kpm}(r) = c^2 - \frac{r_s}{r} c^2 - \frac{c^2}{r^2} (a^2 (E^2 - 1) - L^2) - \frac{r_s c^2}{r^3} (L - a E)^2$$

These relations verify the equations of the geodesics.

Deriving from  $\tau$  the equation  $(K_{pm3})$  and for non-circular orbits, we deduce the following differential equation used to make the simulation :

$$(K_{pm4}) \quad \frac{d^2 r}{d\tau^2} = -\frac{1}{2} \frac{dV_{Kpm}}{dr} = \frac{-c^2}{2r^4} [r_s r^2 + 2r (a^2 (E^2 - 1) - L^2) + 3r_s (L - aE)^2] = f_{Kpm}(r)$$

The equation  $K_{pm4}$  is solved numerically by the Runge-Kutta method.

[Initial values III.7-A.2](#)

## II.3 Photon

We keep relations in  $t$  and  $\varphi$  :

$$(K_{ph1}) \quad \frac{dt}{d\lambda} = \frac{1}{\Delta(r)} \left[ (r^2 + a^2 + \frac{r_s}{r} a^2) E - \frac{r_s a}{r} L \right] \quad \text{and} \quad (K_{ph2}) \quad \frac{d\varphi}{d\lambda} = \frac{c}{\Delta(r)} \left[ \frac{r_s a}{r} E + (1 - \frac{r_s}{r}) L \right]$$

These functions reported in the expression  $ds = 0$  involve :

$$(K_{ph3}) \quad \left( \frac{dr}{d\lambda} \right)^2 + V_{Kph}(r) = c^2 E^2 \quad \text{where} \quad V_{Kph}(r) = -\frac{c^2}{r^2} (a^2 E^2 - L^2) - \frac{r_s c^2}{r^3} (L - a E)^2$$

These relations verify the equations of the geodesics.

By deriving with respect to  $\lambda$  the equation  $(K_{ph3})$  and for non-circular orbits, we deduce the following differential equation used to make the simulation :

$$(K_{ph4}) \quad \frac{d^2 r}{d\lambda^2} = -\frac{1}{2} \frac{dV_{Kph}}{dr} = -\frac{c^2}{2r^4} [2r (a^2 E^2 - L^2) + 3r_s (L - aE)^2] = f_{Kph}(r)$$

There are two unstable circular orbits of radii (see [James M. Bardeen](#) ) :

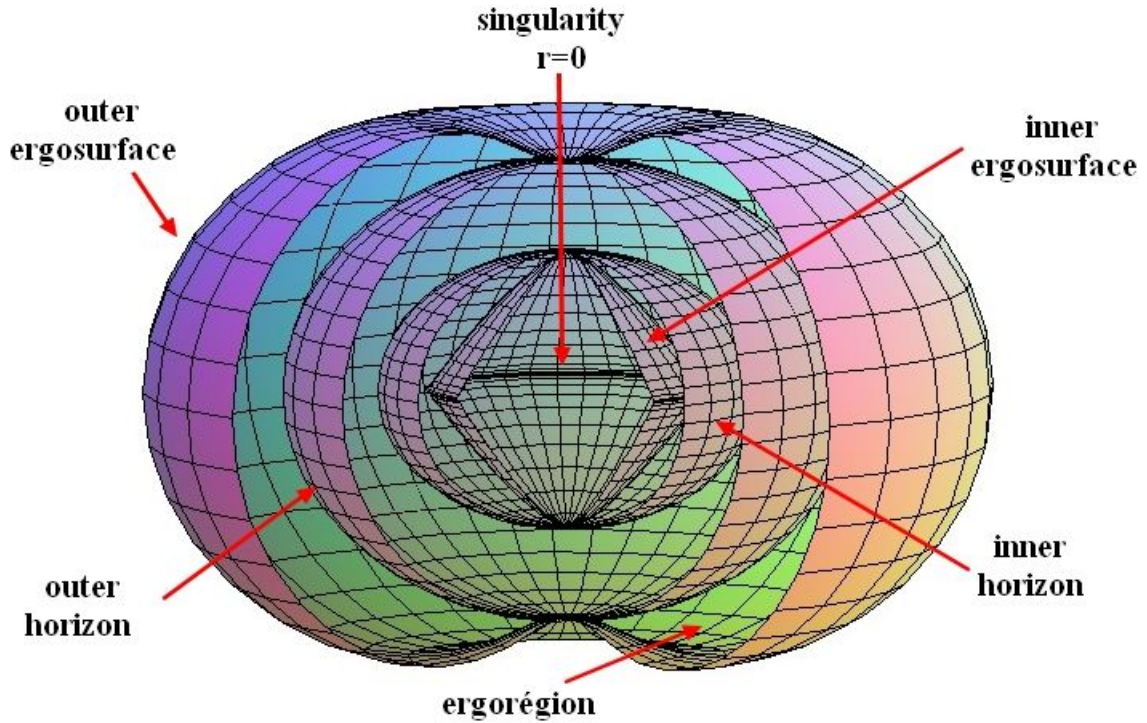
$$r_s \left\{ 1 + \cos \left[ \frac{2}{3} \arccos \left( \frac{2a}{r_s} \right) \right] \right\} \quad \text{and} \quad r_s \left\{ 1 + \cos \left[ \frac{2}{3} \arccos \left( \frac{-2a}{r_s} \right) \right] \right\}$$

The equation  $K_{ph}4$  is solved numerically by the Runge-Kutta method.

[Initial values III.7-A.1](#)

Image of the different horizons and regions of the Kerr metric from outside to inside  
(see [C.Heinicke et F.W.Hehl](#))

- outer ergosurface	$r_{E+} = \frac{r_s}{2} + \sqrt{\frac{r_s^2}{4} - a^2 \cos^2(\theta)}$	$\theta = \frac{\pi}{2} \Rightarrow r_{E+} = r_s$
- outer horizon	$r_+ = \frac{r_s}{2} + \sqrt{\frac{r_s^2}{4} - a^2}$	
- inner horizon	$r_- = \frac{r_s}{2} - \sqrt{\frac{r_s^2}{4} - a^2}$	
- inner ergosurface	$r_{E-} = \frac{r_s}{2} - \sqrt{\frac{r_s^2}{4} - a^2 \cos^2(\theta)}$	



For this figure the coordinates are

$$x = \sqrt{r^2 + a^2} \cos \phi \sin \theta \quad y = \sqrt{r^2 + a^2} \sin \phi \sin \theta \quad z = r \cos \theta$$

## III - Appendix

### III.1 Euler-Lagrange equations

Let  $\mathcal{L}(x^1(\lambda), x^2(\lambda), \dots, x^n(\lambda), \dot{x}^1(\lambda), \dot{x}^2(\lambda), \dots, \dot{x}^n(\lambda))$  a function of  $2n$  independent variables where  $\dot{x}^i = \frac{dx^i}{d\lambda}$ .

So, the value of the integral  $\int_{\lambda_a}^{\lambda_b} \mathcal{L}(\lambda) d\lambda$  is extreme for curves  $\{x^i(\lambda)\}_{i \in \{1, 2, \dots, n\}}$

that verify Euler-Lagrange's equations :

$$\frac{d}{d\lambda} \frac{\partial \mathcal{L}}{\partial \dot{x}^k} - \frac{\partial \mathcal{L}}{\partial x^k} = 0 \quad \forall k \in \{1, 2, \dots, n\}$$

### III.2 Metrics and geodesics

For an exhaustive study see [Ericourgoulhon - Geometry and physics of black holes](#) and [Ericourgoulhon - Relativité générale](#) .

#### *Metrics*

In a space-time, we represent by  $ds^2$  the infinitesimal interval between two events marked by the coordinates  $(x^1, x^2, x^3, x^4 = ct)$  and  $(x^1 + dx^1, x^2 + dx^2, x^3 + dx^3, ct + cdt)$  where

$$ds^2 = \sum_{i=1}^4 \sum_{j=1}^4 g_{ij}(x^1, x^2, x^3, x^4) dx^i dx^j = g_{ij} dx^i dx^j \quad (\text{with Einstein summation notation})$$

By abuse of language, we will speak of « distance » between these two events. The  $4 \times 4$  symmetric matrix of the 16 functions  $g_{ij}$  (coefficients of the metric) allowing an inverse (whose coefficients are noted  $g^{\alpha\beta}$ ) at any point where the metric is defined.

Basic properties of this « distance » :

- It's an invariant for any change in coordinates

$$ds^2 = \sum_{i=1}^4 \sum_{j=1}^4 g_{ij}(x^1, x^2, x^3, x^4) dx^i dx^j = \sum_{i=1}^4 \sum_{j=1}^4 \bar{g}_{pq}(y^1, y^2, y^3, y^4) dy^p dy^q \quad (g_{ij} dx^i dx^j = \bar{g}_{pq} dy^p dy^q)$$

- It's spelled  $ds = c d\tau$  where  $\tau$  is the eigentime measured (by clock) between events  $(x^1, x^2, x^3, x^4)$  and  $(x^1 + dx^1, x^2 + dx^2, x^3 + dx^3, x^4 + dx^4)$

- For a photon, you always have  $ds = 0$

#### *Geodesics*

The curves that make the « distance » between two events in space-time extreme are called geodesics. They verify the differential equations :

$$\frac{d^2 x^k}{d\lambda^2} + \Gamma_{ij}^k \frac{dx^i}{d\lambda} \frac{dx^j}{d\lambda} = 0 \quad k \in \{1, 2, 3, 4\}$$

with the connection coefficients (Christoffel symbols of second kind)

$$\Gamma_{jk}^i = \Gamma_{kj}^i = \frac{1}{2} g^{ip} \left( \frac{\partial g_{pk}}{\partial x^j} + \frac{\partial g_{pj}}{\partial x^k} - \frac{\partial g_{kj}}{\partial x^p} \right)$$



With the function :  $\mathcal{L}(..x^p(\lambda).., ..\dot{x}^q(\lambda)..) = \sqrt{\epsilon g_{ij} \frac{dx^i}{d\lambda} \frac{dx^j}{d\lambda}} = \frac{ds}{d\lambda}$

where  $\epsilon = 1$  for timelike curves ( $ds^2 > 0$ ) and  $\epsilon = -1$  for spacelike curves ( $ds^2 < 0$ ) (for a signature  $- - - +$ ).

The curves  $\{x^k(\lambda)\}_{k \in \{1,2,3,4\}}$  that make the integral  $\int_a^b ds = \int_{\lambda_a}^{\lambda_b} \mathcal{L}(\lambda) d\lambda = s(b) - s(a)$  extreme are the geodesics.

To find first integrals of geodesic equations, we can look for solutions

to Euler-Lagrange's equations :  $\frac{d}{d\lambda} \frac{\partial \mathcal{L}}{\partial \dot{x}^k} - \frac{\partial \mathcal{L}}{\partial x^k} = 0 \quad k \in \{1, 2, 3, 4\}$

### III.3 Application

For Schwarzschild and Kerr metrics the functions  $g_{ij}$  are independent of  $t$  and  $\varphi$  :

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial t} &= 0 \quad \text{and} \quad \frac{\partial \mathcal{L}}{\partial \varphi} = 0 \\ \Rightarrow \quad \frac{\partial \mathcal{L}}{\partial \dot{t}} &= \text{constante1} \quad \text{and} \quad \frac{\partial \mathcal{L}}{\partial \dot{\varphi}} = \text{constante2} \end{aligned}$$

By imposing  $\theta = \frac{\pi}{2}$  the combination of the two previous relationships gives the equations  $S1, S2, K1, K2$ .

### III.4 Runge-Kutta method of order 4

Method for numerically solving the differential equation :  $\frac{d^2 r}{d\lambda^2}(r) = f(r)$

with initial values  $\lambda = \lambda_0$  ,  $r = r_0$  and  $\frac{dr}{d\lambda}(r_0)$ .

We calculate the values  $r_n$  ,  $y'_n = \frac{dr}{d\lambda}(r_n)$  and  $\varphi_n$  starting from  $(r_0, \frac{dr}{d\lambda}(r_0))$  ,  $\varphi_0$  with a  $h$  step for the variable  $\lambda$ .

$$k_1 = f(r_n) \quad , \quad k_2 = f(r_n + \frac{h}{2} y'_n) \quad , \quad k_3 = f(r_n + \frac{h}{2} y'_n + \frac{h^2}{4} k_1) \quad , \quad k_4 = f(r_n + h y'_n + \frac{h^2}{2} k_2)$$

$$r_{n+1} = r_n + h y'_n + \frac{h^2}{6} (k_1 + k_2 + k_3)$$

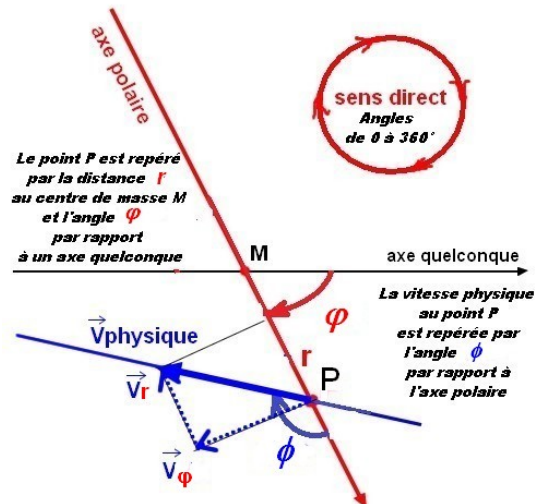
$$y'_{n+1} = y'_n + \frac{h}{6} (k_1 + 2 k_2 + 2 k_3 + k_4)$$

$$\varphi_{n+1} = \varphi_n + d\varphi \quad \text{see} \quad S2 \quad \text{or} \quad K2$$

see [here](#)

### III.5 Physical speed

The physical speed of a moving body passing at the point  $r, \theta, \varphi$  of the space-time is the one which would be measured in an orthonormal référentiel attached to an observer (not to be confused with the "distant observer") located at the point  $r, \theta, \varphi$ .





With  $\theta = \frac{\pi}{2}$  we note :

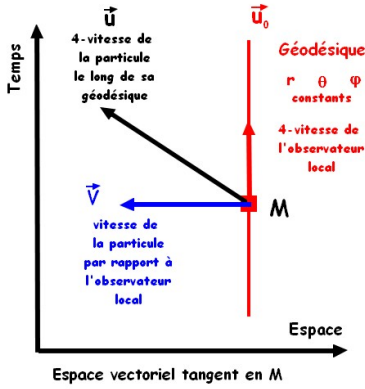
- $r$  and  $\varphi$  the polar coordinates of a point  $P$  of the trajectory (initial values  $r_0$  et  $\varphi_0$ ).
- $\phi$  the polar angle of the physical velocity vector (initial value  $\phi_0$ ).
- $V$  the physical speed module ( $v_0 = V(r_0)$   $\phi_0 = \phi(r_0)$ ).
- $V_r = V \cos(\phi)$  et  $V_\varphi = V \sin(\phi)$  the algebraic values of the physical radial velocity and the physical tangential velocity

### III.6 Physical speed in Schwarzschild metric

The Scharwzschild tensor (internal and external) can be written as :

$$ds^2 = g_{t,t}(r) dt^2 + g_{r,r}(r) dr^2 + g_{\theta,\theta}(r) d\theta^2 + g_{\varphi,\varphi}(r) d\varphi^2$$

in a system of coordinates  $\{t, r, \theta, \varphi\}$ .



At point  $M$ , the observer (zero mass) (geodesic  $r, \theta, \varphi$  constants, with a four-speed  $\vec{u}_0$ ), determine the physical speed  $\vec{V}$  from a particle with a four-speed  $\vec{u}$ .

The generic basis of the tangent vector space in  $M$  shall be noted :  $\{\vec{\partial}_t, \vec{\partial}_r, \vec{\partial}_\theta, \vec{\partial}_\varphi\}$  and an orthonormal basis  $\{\vec{e}^t, \vec{e}^r, \vec{e}^\theta, \vec{e}^\varphi\}$ , so the speed  $\vec{V}$  is written as :

$$\begin{aligned} \vec{V} &= V^r \vec{\partial}_r + V^\theta \vec{\partial}_\theta + V^\varphi \vec{\partial}_\varphi \\ &= V_r \vec{e}^r + V_\theta \vec{e}^\theta + V_\varphi \vec{e}^\varphi \end{aligned}$$

With the obvious orthonormal basis :  $\{\vec{e}^t = \frac{1}{\sqrt{g_{t,t}}} \vec{\partial}_t, \vec{e}^r = \frac{1}{\sqrt{g_{r,r}}} \vec{\partial}_r, \vec{e}^\theta = \frac{1}{\sqrt{g_{\theta,\theta}}} \vec{\partial}_\theta, \vec{e}^\varphi = \frac{1}{\sqrt{g_{\varphi,\varphi}}} \vec{\partial}_\varphi\}$

$$\text{so : } V_r^2 = g_{r,r} V^{r^2} \quad V_\theta^2 = g_{\theta,\theta} V^{\theta^2} \quad V_\varphi^2 = g_{\varphi,\varphi} V^{\varphi^2}$$

The 4-speed of the local observer  $\vec{u}_0 = (\frac{dt}{d\tau_{loc}}, \frac{dr}{d\tau_{loc}}, \frac{d\theta}{d\tau_{loc}}, \frac{d\varphi}{d\tau_{loc}}) = (\frac{c}{\sqrt{g_{t,t}}}, 0, 0, 0)$  and the 4-speed

of the particle  $\vec{u} = (\frac{dt}{d\lambda}, \frac{dr}{d\lambda}, \frac{d\theta}{d\lambda}, \frac{d\varphi}{d\lambda})$  (parameters  $\lambda$  for photons and  $\tau$  for the proper time of other particles).

With hypothesis  $\vec{u} = \Gamma(\vec{u}_0 + \vec{V})$  and the scalar product  $\vec{u}_0 \cdot \vec{V} = 0$  the square of the physical speed is equal to :  $V_r^2 + V_\theta^2 + V_\varphi^2$ .

Calculation for  $\Gamma$  with  $\vec{u} \cdot \vec{u}_0 = \Gamma(\vec{u}_0 \cdot \vec{u}_0 + \vec{u}_0 \cdot \vec{V})$  so :

$$g_{\alpha,\beta} u^\alpha u_0^\beta = g_{t,t} \frac{c}{\sqrt{g_{t,t}}} \frac{dt}{d\lambda} = \Gamma g_{\alpha,\beta} u_0^\alpha u_0^\beta = \Gamma c^2 \quad \implies \quad \Gamma = \frac{\sqrt{g_{t,t}}}{c} \frac{dt}{d\lambda}$$

On the other hand :

$$\Gamma V^r = \frac{dr}{d\lambda} \quad \text{et} \quad V_r^2 = \frac{g_{r,r}}{\Gamma^2} \left( \frac{dr}{d\lambda} \right)^2 \quad \Gamma V^\theta = \frac{d\theta}{d\lambda} \quad \text{et} \quad V_\theta^2 = \frac{g_{\theta,\theta}}{\Gamma^2} \left( \frac{d\theta}{d\lambda} \right)^2 \quad \Gamma V^\varphi = \frac{d\varphi}{d\lambda} \quad \text{et} \quad V_\varphi^2 = \frac{g_{\varphi,\varphi}}{\Gamma^2} \left( \frac{d\varphi}{d\lambda} \right)^2$$

So, expression for the physical speed squared :

$$\frac{c^2}{|g_{t,t}|} \left[ g_{r,r} \left( \frac{dr}{d\lambda} \right)^2 + g_{\theta,\theta} \left( \frac{d\theta}{d\lambda} \right)^2 + g_{\varphi,\varphi} \left( \frac{d\varphi}{d\lambda} \right)^2 \right] \left( \frac{d\lambda}{dt} \right)^2$$

$$= \frac{c^2}{|g_{t,t}|} \left[ g_{r,r} \left( \frac{dr}{dt} \right)^2 + g_{\theta,\theta} \left( \frac{d\theta}{dt} \right)^2 + g_{\varphi,\varphi} \left( \frac{d\varphi}{dt} \right)^2 \right]$$

This method is the formatting of handwritten notes from **Eric Gougoulhon** (presented a conference in Montpellier in 2017).

## A - External Scharwzschild metric - particular case $\theta = \frac{\pi}{2}$

Metric outside a centro-symmetrical star, of mass  $M$ , without rotation.

The coefficients of the metric are :

$$g_{t,t} = -c^2 \left( 1 - \frac{r_s}{r} \right) \quad g_{r,r} = \frac{1}{\left( 1 - \frac{r_s}{r} \right)} \quad g_{\theta,\theta} = 0 \quad g_{\varphi,\varphi} = r^2$$

### A.1 Photons

First integrals :

$$\frac{dt}{d\lambda} = \frac{E}{1 - \frac{r_s}{r}} \quad \frac{d\varphi}{d\lambda} = \frac{c L}{r^2}$$

$$\frac{d\varphi}{dt} = \frac{1}{E} \left( 1 - \frac{r_s}{r} \right) \frac{c L}{r^2} \quad \left( \frac{dr}{dt} \right)^2 = \frac{c^2}{E^2} \left( 1 - \frac{r_s}{r} \right)^2 \left[ E^2 - \left( 1 - \frac{r_s}{r} \right) \frac{L^2}{r^2} \right]$$

Calculation for the **physical speed squared** :

$$\frac{1}{\left( 1 - \frac{r_s}{r} \right)^2} \left[ \left( \frac{dr}{dt} \right)^2 + \left( 1 - \frac{r_s}{r} \right) r^2 \left( \frac{d\varphi}{dt} \right)^2 \right] = c^2$$

### Initial values III.6-A.1

$$V_r(r_0) = c \cos(\phi_0)$$

$$V_\varphi(r_0) = c \sin(\phi_0)$$

so

$$E = 1$$

$$L = \frac{r_0 \sin(\phi_0)}{\sqrt{1 - \frac{r_s}{r_0}}}$$

### A.2 Other particles

First integrals :

$$\frac{dt}{d\tau} = \frac{E}{1 - \frac{r_s}{r}} \quad \frac{d\varphi}{d\tau} = \frac{c L}{r^2}$$

$$\frac{d\varphi}{dt} = \frac{1}{E} \left( 1 - \frac{r_s}{r} \right) \frac{c L}{r^2} \quad \left( \frac{dr}{dt} \right)^2 = \frac{c^2}{E^2} \left( 1 - \frac{r_s}{r} \right)^2 \left[ E^2 - \left( 1 - \frac{r_s}{r} \right) \left( 1 + \frac{L^2}{r^2} \right) \right]$$

Calculation for the **physical speed squared** :

$$\frac{1}{\left( 1 - \frac{r_s}{r} \right)^2} \left[ \left( \frac{dr}{dt} \right)^2 + \left( 1 - \frac{r_s}{r} \right) r^2 \left( \frac{d\varphi}{dt} \right)^2 \right] = \frac{c^2}{E^2} \left[ E^2 - \left( 1 - \frac{r_s}{r} \right) \right]$$

### Initial values III.6-A.2

$$V_r(r_0) = v_0 \cos(\phi_0)$$

$$V_\varphi(r_0) = v_0 \sin(\phi_0)$$

so

$$E = \frac{\sqrt{1 - \frac{r_s}{r_0}}}{\sqrt{1 - \frac{v_0^2}{c^2}}} \quad L = \frac{v_0}{c} \frac{r_0 E \sin(\phi_0)}{\sqrt{1 - \frac{r_s}{r_0}}}$$

## B - Internal Scharwzschild metric - particular case $\theta = \frac{\pi}{2}$

Metric inside a star of radius  $R$ , mass  $M$ , constant density , without rotation.

The coefficients of the metric are :

$$g_{t,t} = -c^2 \left[ \frac{3}{2} \sqrt{1 - \frac{r_s}{R}} - \frac{1}{2} \sqrt{1 - \frac{r^2 r_s}{R^3}} \right]^2 \quad g_{r,r} = \frac{1}{1 - \frac{r^2 r_s}{R^3}} \quad g_{\theta,\theta} = 0 \quad g_{\varphi,\varphi} = r^2$$

With  $\alpha(r) = 1 - \frac{r^2 r_s}{R^3} \quad \beta(r) = \frac{3}{2} \sqrt{1 - \frac{r_s}{R}} - \frac{1}{2} \sqrt{1 - \frac{r^2 r_s}{R^3}}$

### B.1 Photons

First integrals :

$$\beta(r)^2 \frac{dt}{d\lambda} = E \quad \frac{d\varphi}{d\lambda} = \frac{cL}{r^2}$$

$$\frac{d\varphi}{dt} = \frac{\beta(r)^2}{E} \frac{cL}{r^2} \quad \left( \frac{dr}{dt} \right)^2 = \frac{c^2}{E^2} \alpha(r) \beta(r)^4 \left[ \frac{E^2}{\beta(r)^2} - \frac{L^2}{r^2} \right]$$

Calculation for the **physical speed squared** :

$$\frac{1}{\beta(r)^2 \alpha(r)} \left[ \left( \frac{dr}{dt} \right)^2 + \alpha(r) r^2 \left( \frac{d\varphi}{dt} \right)^2 \right] = c^2$$

### **Initial values III.6-B.1**

$$V_r(r_0) = c \cos(\phi_0) \quad V_\varphi(r_0) = c \sin(\phi_0)$$

so

$$E = 1 \quad L = \frac{r_0 \sin(\phi_0)}{\beta(r_0)}$$

### B.2 Other particles

First integrals :

$$\beta(r)^2 \frac{dt}{d\tau} = E \quad \frac{d\varphi}{d\tau} = \frac{cL}{r^2}$$

$$\frac{d\varphi}{dt} = \frac{\beta(r)^2}{E} \frac{cL}{r^2} \quad \left( \frac{dr}{dt} \right)^2 = \frac{c^2}{E^2} \alpha(r) \beta(r)^4 \left[ \frac{E^2}{\beta(r)^2} - \frac{L^2}{r^2} - 1 \right]$$

Calculation for the **physical speed squared** :

$$\frac{1}{\beta(r)^2 \alpha(r)} \left[ \left( \frac{dr}{dt} \right)^2 + \alpha(r) r^2 \left( \frac{d\varphi}{dt} \right)^2 \right] = \frac{c^2}{E^2} [E^2 - \beta(r)^2]$$

$$V_r(r_0) = v_0 \cos(\phi_0)$$

$$V_\varphi(r_0) = v_0 \sin(\phi_0)$$

d'où

$$E = \frac{\beta(r_0)}{\sqrt{1 - \frac{v_0^2}{c^2}}}$$

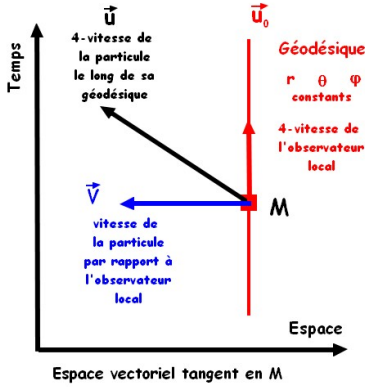
$$L = \frac{v_0}{c} \frac{r_0 \sin \phi_0}{\sqrt{1 - \frac{v_0^2}{c^2}}}$$

### III.7 Physical speed in Kerr metric

The Kerr tensor can be written as :

$$ds^2 = g_{t,t}(r) dt^2 + g_{t,\varphi}(r) dt d\varphi + g_{\varphi,t}(r) d\varphi dt + g_{r,r}(r) dr^2 + g_{\theta,\theta}(r) d\theta^2 + g_{\varphi,\varphi}(r) d\varphi^2$$

in a system of coordinates  $\{t, r, \theta, \varphi\}$ .



At point  $M$ , the observer (zero mass) (geodesic  $r, \theta, \varphi$  constants, with a four-speed  $\vec{u}_0$ ), determine the physical speed  $\vec{V}$  from a particle with a four-speed  $\vec{u}$ .

The generic basis of the tangent vector space in  $M$  shall be noted :  $\{\vec{\partial}_t, \vec{\partial}_r, \vec{\partial}_\theta, \vec{\partial}_\varphi\}$  and an orthonormal basis  $\{\vec{e}^t, \vec{e}^r, \vec{e}^\theta, \vec{e}^\varphi\}$ , so the speed  $\vec{V}$  is written as :

$$\begin{aligned} \vec{V} &= V^r \vec{\partial}_r + V^\theta \vec{\partial}_\theta + V^\varphi \vec{\partial}_\varphi \\ &= V_r \vec{e}^r + V_\theta \vec{e}^\theta + V_\varphi \vec{e}^\varphi \end{aligned}$$

With the orthonormal basis :

$$\begin{aligned} \left\{ \begin{aligned} \vec{e}^t &= \frac{1}{\sqrt{g_{t,t}}} \vec{\partial}_t & \vec{e}^r &= \frac{1}{\sqrt{g_{r,r}}} \vec{\partial}_r & \vec{e}^\theta &= \frac{1}{\sqrt{g_{\theta,\theta}}} \vec{\partial}_\theta \\ \vec{e}^\varphi &= \frac{-g_{t,\varphi}}{g_{t,t} \sqrt{\frac{g_{t,t} g_{\varphi,\varphi} - g_{t,\varphi} g_{\varphi,t}}{g_{t,t}}}} \vec{\partial}_t + \frac{1}{\sqrt{\frac{g_{t,t} g_{\varphi,\varphi} - g_{t,\varphi} g_{\varphi,t}}{g_{t,t}}}} \vec{\partial}_\varphi \end{aligned} \right\} \end{aligned}$$

$$\text{so :} \quad V_r^2 = g_{r,r} V^{r2} \quad V_\theta^2 = g_{\theta,\theta} V^{\theta2} \quad V_\varphi^2 = \frac{(g_{t,t} g_{\varphi,\varphi} - g_{t,\varphi} g_{\varphi,t})}{g_{t,t}} V^{\varphi2}$$

The 4-speed of the local observer  $\vec{u}_0 = (\frac{dt}{d\tau_{loc}}, \frac{dr}{d\tau_{loc}}, \frac{d\theta}{d\tau_{loc}}, \frac{d\varphi}{d\tau_{loc}}) = (\frac{c}{\sqrt{g_{t,t}}}, 0, 0, 0)$  and the 4-speed of the particle  $\vec{u} = (\frac{dt}{d\lambda}, \frac{dr}{d\lambda}, \frac{d\theta}{d\lambda}, \frac{d\varphi}{d\lambda})$  ( parameters  $\lambda$  for photons and  $\tau$  for the proper time of other particles).

With hypothesis  $\vec{u} = \Gamma(\vec{u}_0 + \vec{V})$  and the scalar product  $\vec{u}_0 \cdot \vec{V} = 0$  the square of the physical speed is equal to :  $V_r^2 + V_\theta^2 + V_\varphi^2$ .

Calculation for  $\Gamma$  with  $\vec{u} \cdot \vec{u}_0 = \Gamma(\vec{u}_0 \cdot \vec{u}_0 + \vec{u}_0 \cdot \vec{V})$  so :

$$g_{\alpha,\beta} u^\alpha u^\beta = g_{t,t} \frac{c}{\sqrt{g_{t,t}}} \frac{dt}{d\lambda} + g_{t,\varphi} \frac{c}{\sqrt{g_{t,t}}} \frac{d\varphi}{d\lambda} = \Gamma g_{\alpha,\beta} u_0^\alpha u_0^\beta = \Gamma c^2 \implies \Gamma = \frac{1}{c} [\sqrt{g_{t,t}} \frac{dt}{d\lambda} + \frac{g_{t,\varphi}}{\sqrt{g_{t,t}}} \frac{d\varphi}{d\lambda}]$$

On the other hand :

$$\Gamma V^r = \frac{dr}{d\lambda} \quad \text{et} \quad V_r^2 = \frac{g_{r,r}}{\Gamma^2} \left( \frac{dr}{d\lambda} \right)^2 \quad \Gamma V^\theta = \frac{d\theta}{d\lambda} \quad \text{et} \quad V_\theta^2 = \frac{g_{\theta,\theta}}{\Gamma^2} \left( \frac{d\theta}{d\lambda} \right)^2$$

$$\Gamma V^\varphi = \frac{d\varphi}{d\lambda} \quad \text{et} \quad V_\varphi^2 = \frac{(g_{t,t} g_{\varphi,\varphi} - g_{t,\varphi} g_{\varphi,t})}{\Gamma^2 g_{t,t}} \left( \frac{d\varphi}{d\lambda} \right)^2$$

So, expression for the **physical speed squared** :

$$\begin{aligned} & \frac{c^2}{\left( \sqrt{g_{t,t}} \frac{dt}{d\lambda} + \frac{g_{t,\varphi}}{\sqrt{g_{t,t}}} \frac{d\varphi}{d\lambda} \right)^2} \left[ g_{r,r} \left( \frac{dr}{d\lambda} \right)^2 + g_{\theta,\theta} \left( \frac{d\theta}{d\lambda} \right)^2 + \frac{(g_{t,t} g_{\varphi,\varphi} - g_{t,\varphi} g_{\varphi,t})}{g_{t,t}} \left( \frac{d\varphi}{d\lambda} \right)^2 \right] \\ &= \frac{c^2}{\left( \sqrt{g_{t,t}} + \frac{g_{t,\varphi}}{\sqrt{g_{t,t}}} \frac{d\varphi}{dt} \right)^2} \left[ g_{r,r} \left( \frac{dr}{dt} \right)^2 + g_{\theta,\theta} \left( \frac{d\theta}{dt} \right)^2 + \frac{(g_{t,t} g_{\varphi,\varphi} - g_{t,\varphi} g_{\varphi,t})}{g_{t,t}} \left( \frac{d\varphi}{dt} \right)^2 \right] \end{aligned}$$

This is an application of the written method in handwritten notes from **Eric Gougoulhon** (presented a conference in Montpellier in 2017).

## A - Kerr metric

Metric outside a centro-symmetric black hole, of mass  $M$ , with constant rotation.

The coefficients of the metric are :

$$\begin{aligned} g_{t,t} &= -c^2 \left( 1 - \frac{r_s r}{\rho^2} \right) & g_{t,\varphi} &= g_{\varphi,t} = -\frac{c r_s a r}{\rho^2} \sin^2(\theta) \\ g_{r,r} &= \frac{\rho^2}{\Delta} & g_{\theta,\theta} &= \rho^2 & g_{\varphi,\varphi} &= \left[ r^2 + a^2 + \frac{r_s a^2 r}{\rho^2} \sin^2(\theta) \right] \sin^2(\theta) \\ \rho^2 &= r^2 + a^2 \cos^2 \theta & \Delta &= r^2 - r_s r + a^2 \end{aligned}$$

### A.1 Photons - Particular case $\theta = \frac{\pi}{2}$

First integrals :

$$\begin{aligned} \frac{dt}{d\lambda} &= \frac{1}{\Delta} \left[ \left( r^2 + a^2 + \frac{r_s}{r} a^2 \right) E - \frac{r_s a}{r} L \right] & \frac{d\varphi}{d\lambda} &= \frac{c}{\Delta} \left[ \frac{r_s a}{r} E + \left( 1 - \frac{r_s}{r} \right) L \right] \\ \frac{d\varphi}{dt} &= \frac{c \left[ \frac{r_s a}{r} E + \left( 1 - \frac{r_s}{r} \right) L \right]}{\left[ \left( r^2 + a^2 + \frac{r_s}{r} a^2 \right) E - \frac{r_s a}{r} L \right]} \\ \left( \frac{dr}{dt} \right)^2 &= c^2 \frac{\left[ E^2 + \frac{(a^2 E^2 - L^2)}{r^2} + r_s \frac{(L - a E)^2}{r^3} \right] (a^2 + r^2 - r r_s)^2}{\left[ \left( r^2 + a^2 + \frac{r_s}{r} a^2 \right) E - \frac{r_s a}{r} L \right]^2} \end{aligned}$$

Calculation for the **physical speed squared** :

$$\frac{\left( 1 - \frac{r_s}{r} \right)}{\left[ \left( 1 - \frac{r_s}{r} \right) + \frac{r_s a}{c r} \left( \frac{d\varphi}{dt} \right) \right]^2} \left[ \frac{r^2}{\Delta} \left( \frac{dr}{dt} \right)^2 + \frac{\Delta}{\left( 1 - \frac{r_s}{r} \right)} \left( \frac{d\varphi}{dt} \right)^2 \right] = \boxed{c^2}$$

**Initial values III.7-A.1**

$$V_r(r_0) = c \cos(\phi_0) \quad V_\varphi(r_0) = c \sin(\phi_0)$$

d'où

$$E = 1 \quad L = \frac{1}{(r_0 - r_s)} \left[ r_0 \sin(\phi_0) \sqrt{\Delta(r_0)} - a r_s \right]$$

**A.2 Other particles - Particular case  $\theta = \frac{\pi}{2}$**

First integrals :

$$\frac{dt}{d\tau} = \frac{1}{\Delta} \left[ (r^2 + a^2 + \frac{r_s}{r} a^2) E - \frac{r_s a}{r} L \right] \quad \frac{d\varphi}{d\tau} = \frac{c}{\Delta} \left[ \frac{r_s a}{r} E + (1 - \frac{r_s}{r}) L \right]$$

$$\frac{d\varphi}{dt} = \frac{c \left[ \frac{r_s a}{r} E + (1 - \frac{r_s}{r}) L \right]}{\left[ (r^2 + a^2 + \frac{r_s}{r} a^2) E - \frac{r_s a}{r} L \right]}$$

$$\left( \frac{dr}{dt} \right)^2 = c^2 \frac{\left[ E^2 - 1 + \frac{r_s}{r} + \frac{(a^2(E^2 - 1) - L^2)}{r^2} + r_s \frac{(L - aE)^2}{r^3} \right] (a^2 + r^2 - r r_s)^2}{\left[ (r^2 + a^2 + \frac{r_s}{r} a^2) E - \frac{r_s a}{r} L \right]^2}$$

Calculation for the **physical speed squared** :

$$\frac{(1 - \frac{r_s}{r})}{\left[ (1 - \frac{r_s}{r}) + \frac{r_s a}{c r} \left( \frac{d\varphi}{dt} \right) \right]^2} \left[ \frac{r^2}{\Delta} \left( \frac{dr}{dt} \right)^2 + \frac{\Delta}{(1 - \frac{r_s}{r})} \left( \frac{d\varphi}{dt} \right)^2 \right] = \frac{c^2}{E^2} \left[ E^2 - (1 - \frac{r_s}{r}) \right]$$

**Initial values III.7-A.2**

$$V_r(r_0) = v_0 \cos(\phi_0) \quad V_\varphi(r_0) = v_0 \sin(\phi_0)$$

so

$$E = c \sqrt{\frac{r_0 - r_s}{r_0 (c^2 - v_0^2)}} \quad L = \frac{-1}{\sqrt{(c^2 - v_0^2)(r_0 - r_s)}} \left[ \frac{a c r_s}{\sqrt{r_0}} - v_0 \sin(\phi_0) \sqrt{r_0 \Delta(r_0)} \right]$$

### III.8 Circular orbits in Kerr and Scharwzschild metrics

#### III.8.1 Kerr metric

**A - particles :**

S.Chandrasekhar in his book : The Mathematical Theory of black hole (pages 333 to 335) which can be downloaded from this address : [https://www.academia.edu/58309424/S\\_Chandrasekhar\\_The\\_Mathematical\\_Theory\\_of\\_Black\\_Holes\\_Oxford\\_University\\_Press\\_1983\\_](https://www.academia.edu/58309424/S_Chandrasekhar_The_Mathematical_Theory_of_Black_Holes_Oxford_University_Press_1983_)

poses (relation 113 where  $M = \frac{r_s}{2}$ ) :

$$u = \frac{1}{r} \quad Q_+(u) = 1 - \frac{3r_s}{2}u + 2a\sqrt{\frac{r_s}{2}}\sqrt{u^3} \quad Q_-(u) = 1 - \frac{3r_s}{2}u - 2a\sqrt{\frac{r_s}{2}}\sqrt{u^3}$$

and the values of constants  $E$  and  $L$  (equations 117 and 118) for a circular trajectory with radius  $u_0 = \frac{1}{r_0}$  are :

$$(I) \quad E_+ = \frac{1 - r_s u_0 + a\sqrt{\frac{r_s}{2}}\sqrt{u_0^3}}{\sqrt{Q_+(u_0)}} \quad (II) \quad L_+ = \frac{\sqrt{\frac{r_s}{2}}}{\sqrt{u_0 Q_+(u_0)}}(a^2 u_0^2 + 1 - 2a\sqrt{\frac{r_s}{2}}\sqrt{u_0^3})$$

$$E_- = \frac{1 - r_s u_0 - a\sqrt{\frac{r_s}{2}}\sqrt{u_0^3}}{\sqrt{Q_-(u_0)}} \quad L_- = \frac{\sqrt{\frac{r_s}{2}}}{\sqrt{u_0 Q_-(u_0)}}(a^2 u_0^2 + 1 + 2a\sqrt{\frac{r_s}{2}}\sqrt{u_0^3})$$

The signs of  $Q_+(u_0)$  and  $Q_-(u_0)$  determine the existence of these circular orbits.

$$\text{If } r_0 \geq r_s$$

$Q_-(u_0) > 0$  ( $\Rightarrow Q_+(u_0) > 0$ ) prograde orbit ( $V_1$ ) and retrograde orbit ( $V_2 > V_1$ )

$Q_-(u_0) < 0$  et  $Q_+(u_0) > 0$  prograde orbit

The values of  $E$ ,  $L$  and the velocities on these circular orbits are correctly calculated in the code.

Exemple 1 :

$$M = 2e39 \quad r_s = 2.970e + 12 \quad J = 8e59 \quad a = 1.334e + 12$$

$$\begin{array}{llllllll} r_0 = 8e12 & E_+ = 9.146e - 1 & L_+ = 3.978e + 12 & V_1 = 1.49393e + 8 & \Phi_0 = 90^\circ & \text{stable} \\ r_0 = 8e12 & E_- = 1.018 & L_- = -7.381e + 12 & V_2 = 1.87950e + 8 & \Phi_0 = -90^\circ & \text{unstable} \\ Q_- \text{ cancels for } r_0 = 5.8048e12 & & Q_+ \text{ cancels for } r_0 = 7.8449e11 \text{ and } r_0 = 2.3214e12. \end{array}$$

$$r_0 = 5e12 \quad E_+ = 8.720e - 1 \quad L_+ = 3.363e + 12 \quad V = 2.04690e + 8 \quad \Phi_0 = 90^\circ \quad \text{stable}$$

Exemple 2 :

$$M = 2e39 \quad r_s = 2.970e + 12 \quad J = 0 \quad a = 0$$

$$\begin{array}{llllllll} r_0 = 5e12 & E_+ = 6.462e - 1 & L_+ = 8.458e + 11 & V = 2.56439e + 8 & \Phi_0 = 90^\circ & \text{unstable} \\ r_0 = 5e12 & E_- = 6.462e - 1 & L_- = 8.458e + 11 & V = 2.56439e + 8 & \Phi_0 = -90^\circ & \text{unstable} \\ Q_- \text{ and } Q_+ \text{ cancel for } r_0 = \frac{3r_s}{2} = 4.4554e12 \text{ and } V = c. \end{array}$$

In this case, there are no circular orbits with  $r_0 < \frac{3r_s}{2}$



$$If \quad r_{H+} < r_0 < r_s$$

Note :  $Q_-(u_0)$  is always negative ; hence, eventually, only one circular orbit.

We know that it is no longer possible to measure velocities. But circular orbits of radius  $r_0$  may or may not exist if the following conditions are met :

$$\begin{aligned} Q_+(u_0) &> 0 && \text{prograde orbit} \\ Q_+(u_0) &< 0 && \text{no prograde orbit} \end{aligned}$$

Exemple 1 :

$$\begin{aligned} M &= 2e39 & r_s &= 2.970e + 12 & J &= 8e59 & a &= 1.334e + 12 \\ r_0 &= 2.5e12 & E_+ &= 1.1109 & L_+ &= 4.422e + 12 & \Phi_0 &= 90^\circ \end{aligned}$$

$Q_+$  cancels out for  $r_0 = 2.321401803e + 12$

$$r_0 = 2.3e12 \quad E \text{ et } L \text{ not calculable} \quad \text{no circular orbit}$$

Exemple 2 :

$$\begin{aligned} M &= 2e39 & r_s &= 2.970e + 12 & J &= 8.9e59 & a &= 1.484e + 12 \\ r_0 &= 1.8e12 & E_+ &= 0.6538 & L_+ &= 1.966e + 12 & \Phi_0 &= 90^\circ \end{aligned}$$

$Q_+$  cancels out for  $r_0 = 1.54075565e + 12$

$$r_0 = 1.50e12 \quad E \text{ et } L \text{ not calculable} \quad \text{no circular orbit}$$

The stability (or not) of the trajectories can be “read” from the potential graph.

**B - photon**

There are two unstable circular ray paths (see [James M. Bardeen](#)) :

$$r_s \left\{ 1 + \cos \left[ \frac{2}{3} \arccos \left( \frac{2a}{r_s} \right) \right] \right\} \quad \text{rétrograde} \quad \text{and} \quad r_s \left\{ 1 - \cos \left[ \frac{2}{3} \arccos \left( \frac{2a}{r_s} \right) \right] \right\} \quad \text{prograde}$$

Exemple :

$$M = 2 \cdot 10^{30} \text{ kg} \quad J = 8.4 \cdot 10^{41} \text{ kg.m}^2.\text{s}^{-1} \quad r_0 = 2097.93 \text{ m} \quad \Phi_0 = 90^\circ \quad r_0 = 5865.32 \text{ m} \quad \Phi_0 = -90^\circ$$

### III.8.2 Métrique de Scharwzschild

**A - projectiles :**

In the relations found for the Kerr metric,  $a = 0$  is used to obtain the speed on the only circular trajectory of radius  $ISCO > \frac{3}{2} r_s$  with  $\Phi_0 = 90^\circ$  where  $\Phi_0 = -90^\circ$  :

$$V_{ISCO} = c \sqrt{\frac{r_s}{2(ISCO - r_s)}}$$

There is a particular value  $ISCO_{par} = 3r_s$  such that :

$$si \quad \frac{3}{2} r_s < ISCO < 3r_s \quad \text{unstable} \quad si \quad ISCO > 3r_s \quad \text{stable}$$

**Exemples :**

$$M = 2 \cdot 10^{30} \text{ kg} \quad ISCO = 10000 \text{ m} \quad V_{ISCO} = 1.3779 \cdot 10^8 \text{ m.s}^{-1} \quad \textit{stable}$$

$$M = 2 \cdot 10^{30} \text{ kg} \quad ISCO = 6000 \text{ m} \quad V_{ISCO} = 2.09894 \cdot 10^8 \text{ m.s}^{-1} \quad \textit{unstable}$$

$$M = 2 \cdot 10^{30} \text{ kg} \quad ISCO_{par} = 8910.79149 \text{ m} \quad V_{ISCO_{par}} = \frac{c}{2}$$

**B - photon**

**Radius of unstable circular orbit**  $r_c = \frac{3}{2}r_s$  **whit**  $\Phi_0 = 90^\circ$  **or**  $\Phi_0 = -90^\circ$ .