

# Geometric Mechanics

## Homework 12

Due on December 14

1. In this exercise we study in detail the timelike and null geodesics of the Schwarzschild space-time. By symmetry, it suffices to study the geodesics of the totally geodesic 3-dimensional Lorentzian submanifold  $\theta = \frac{\pi}{2}$  (**equatorial plane**), whose metric is

$$g = - \left(1 - \frac{2m}{r}\right) dt \otimes dt + \left(1 - \frac{2m}{r}\right)^{-1} dr \otimes dr + r^2 d\varphi \otimes d\varphi.$$

- (a) Show that the equations for a future-directed geodesic (parameterized by proper time if timelike) can be written as

$$\begin{cases} \dot{r}^2 = E^2 - \left(\sigma + \frac{L^2}{r^2}\right) \left(1 - \frac{2m}{r}\right) \\ \left(1 - \frac{2m}{r}\right) \dot{t} = E \\ r^2 \dot{\varphi} = L \end{cases}$$

where  $E > 0$  and  $L$  are integration constants,  $\sigma = 1$  for timelike geodesics and  $\sigma = 0$  for null geodesics.

- (b) Show that if  $L \neq 0$  then  $u = \frac{1}{r}$  satisfies

$$\frac{d^2 u}{d\varphi^2} + u = \frac{m\sigma}{L^2} + 3mu^2.$$

- (c) For situations where relativistic corrections are small one has  $mu \ll 1$ , and hence the approximate equation

$$\frac{d^2 u}{d\varphi^2} + u = \frac{m}{L^2}$$

holds for timelike geodesics. Show that the solution to this equation is the conic section given in polar coordinates by

$$u = \frac{m}{L^2} (1 + \varepsilon \cos(\varphi - \varphi_0)),$$

where the integration constants  $\varepsilon \geq 0$  and  $\varphi_0$  are the eccentricity and the argument of the pericenter.

- (d) Show that for  $\varepsilon \ll 1$  this approximate solution satisfies

$$u^2 \simeq \frac{2m}{L^2} u - \frac{m^2}{L^4}.$$

Argue that timelike geodesics close to circular orbits where relativistic corrections are small yield approximate solutions of the equation

$$\frac{d^2 u}{d\varphi^2} + \left(1 - \frac{6m^2}{L^2}\right) u = \frac{m}{L^2} \left(1 - \frac{3m^2}{L^2}\right),$$

and hence the pericenter advances by approximately

$$\frac{6\pi m}{r}$$

radians per revolution. (**Remark:** The first success of general relativity was due to this effect, which explained the anomalous **precession of Mercury's perihelion** – 43 arcseconds per century).

- (e) Show that if one neglects relativistic corrections then null geodesics satisfy

$$\frac{d^2 u}{d\varphi^2} + u = 0.$$

Show that the solution to this equation is the equation for a straight line in polar coordinates,

$$u = \frac{1}{b} \sin(\varphi - \varphi_0),$$

where the integration constants  $b > 0$  and  $\varphi_0$  are the **impact parameter** (distance of closest approach to the center) and the angle between the line and the  $x$ -axis.

- (f) Assume that  $mu \ll 1$ . Let us include relativistic corrections by looking for approximate solutions of the form

$$u = \frac{1}{b} \left( \sin \varphi + \frac{m}{b} v \right)$$

(where we take  $\varphi_0 = 0$  for simplicity). Show that  $v$  is an approximate solution of the equation

$$\frac{d^2 v}{d\varphi^2} + v = 3 \sin^2 \varphi,$$

and hence  $u$  is approximately given by

$$u = \frac{1}{b} \left( \sin \varphi + \frac{m}{b} \left( \frac{3}{2} + \frac{1}{2} \cos(2\varphi) + \alpha \cos \varphi + \beta \sin \varphi \right) \right),$$

where  $\alpha$  and  $\beta$  are integration constants.

- (g) Show that for the incoming part of the null geodesic ( $\varphi \simeq 0$ ) one approximately has

$$u = 0 \Leftrightarrow \varphi = -\frac{m}{b} (2 + \alpha).$$

Similarly, show that for the outgoing part of the null geodesic ( $\varphi \simeq \pi$ ) one approximately has

$$u = 0 \Leftrightarrow \varphi = \pi + \frac{m}{b} (2 - \alpha).$$

Conclude that  $\varphi$  varies by approximately

$$\Delta\varphi = \pi + \frac{4m}{b}$$

radians along its path, and hence the null geodesic is deflected towards the center by approximately

$$\frac{4m}{b}$$

radians. (**Remark:** The measurement of this **deflection of light** by the Sun – 1.75 arcseconds – was the first experimental confirmation of general relativity, and made Einstein a world celebrity overnight).