

PHOTON EQUATIONS OF MOTION

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Reference: Moore, Thomas A., *A General Relativity Workbook*, University Science Books (2013) - Chapter 12; Problems 12.1, 12.2.

The main problem in applying the geodesic equation to photons is that for photons, $d\tau$ is always zero (that is, the proper time in the frame of the photon never changes). The geodesic equation makes explicit reference to τ :

$$(1) \quad \frac{d}{d\tau} \left(g_{aj} \frac{dx^j}{d\tau} \right) - \frac{1}{2} \frac{\partial g_{ij}}{\partial x^a} \frac{dx^i}{d\tau} \frac{dx^j}{d\tau} = 0$$

The resolution of this problem is typical of the approach to relativity: find some equations for ordinary particles (that is, particles with rest mass) that *don't* depend on τ or m (since photons have no rest mass, we can't have mass showing up in the equations either), and then *assume* that these equations are valid for photons too.

We can start with the conserved quantities in the Schwarzschild metric:

$$(2) \quad e = \left(1 - \frac{2GM}{r} \right) \frac{dt}{d\tau}$$

$$(3) \quad l = r^2 \sin^2 \theta \frac{d\phi}{d\tau}$$

These quantities both make reference to τ but their *ratio* doesn't. If we further assume that motion is in the equatorial plane so that $\theta = \pi/2$, then we get

$$(4) \quad \frac{l}{e} = \frac{r^2 \frac{d\phi}{d\tau}}{\left(1 - \frac{2GM}{r} \right) \frac{dt}{d\tau}}$$

$$(5) \quad = \left(1 - \frac{2GM}{r} \right)^{-1} r^2 \frac{d\phi}{dt}$$

where t is now the Schwarzschild time coordinate. Thus one equation of motion is

$$(6) \quad \frac{d\phi}{dt} = \frac{1}{r^2} \left(1 - \frac{2GM}{r}\right) b$$

where $b \equiv l/e$.

A second equation can be derived starting from the Schwarzschild metric definition:

$$(7) \quad ds^2 = - \left(1 - \frac{2GM}{r}\right) dt^2 + \left(1 - \frac{2GM}{r}\right)^{-1} dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2$$

For a photon, $ds^2 = 0$, and since we're restricting motion to the equatorial plane $d\theta = 0$, so

$$(8) \quad - \left(1 - \frac{2GM}{r}\right) dt^2 + \left(1 - \frac{2GM}{r}\right)^{-1} dr^2 + r^2 d\phi^2 = 0$$

Dividing through by $\left(1 - \frac{2GM}{r}\right) dt^2$ and using 6, we get

$$(9) \quad \left[\left(1 - \frac{2GM}{r}\right)^{-1} \frac{dr}{dt} \right]^2 + \left(1 - \frac{2GM}{r}\right)^{-1} r^2 \left(\frac{d\phi}{dt}\right)^2 = 1$$

$$(10) \quad \left[\left(1 - \frac{2GM}{r}\right)^{-1} \frac{dr}{dt} \right]^2 + \left(1 - \frac{2GM}{r}\right) \frac{b^2}{r^2} = 1$$

$$(11) \quad \left[\frac{1}{b} \left(1 - \frac{2GM}{r}\right)^{-1} \frac{dr}{dt} \right]^2 + \frac{1}{r^2} \left(1 - \frac{2GM}{r}\right) = \frac{1}{b^2}$$

This last equation is the equation of motion for r .

If we interpret this as a sort of kinetic energy plus potential energy equation, we can define the pseudo-kinetic energy as

$$(12) \quad K \equiv \left[\frac{1}{b} \left(1 - \frac{2GM}{r}\right)^{-1} \frac{dr}{dt} \right]^2$$

and the pseudo-potential energy as

$$(13) \quad U(r) \equiv \frac{1}{r^2} \left(1 - \frac{2GM}{r}\right)$$

The potential energy has a zero at $r = 2GM$ and a maximum found from its derivative

$$(14) \quad \frac{dU}{dr} = -\frac{2}{r^3} + \frac{6GM}{r^4} = 0$$

$$(15) \quad r = 3GM$$

$$(16) \quad U_{max} = \frac{1}{27G^2M^2}$$

The ratio $l/e = b$ must be specified in order for the equations of motion to be solved. We can put a geometric interpretation on b , which helps us to understand what the equations of motion are saying. First, draw a ray from $r = 0$ out to infinity, and suppose a photon starts at infinity and follows an initial path that is parallel to this ray, but at a perpendicular distance d from it. Now draw a triangle with one side being the line from $r = 0$ to the photon, a second side being along the ray we drew at the start, and the third side being the perpendicular line of length d that goes from the photon's path to the ray. For large r , the first two sides of the triangle will be almost the same length, and the angle ϕ subtended by the side d will be very small, so that $\sin \phi \approx \phi \approx d/r$. Taking the derivative, we get

$$(17) \quad \frac{d\phi}{dt} = -\frac{d}{r^2} \frac{dr}{dt}$$

From the equation of motion for r , at very large r

$$(18) \quad \frac{1}{b^2} \left(\frac{dr}{dt} \right)^2 \approx \frac{1}{b^2}$$

$$(19) \quad \frac{dr}{dt} \approx \pm 1$$

This isn't terribly surprising, since at very large r , space is essentially flat, so the speed of the photon is just dr/dt which is the speed of light. Putting this into the previous equation, we get (taking $dr/dt = -1$ for an incoming photon):

$$(20) \quad \frac{d\phi}{dt} = -\frac{d}{r^2} \frac{dr}{dt} = \frac{d}{r^2}$$

However, from 6 at very large r $d\phi/dt \approx b/r^2$, so it seems that $b = d$, that is, b is what is known as the *impact parameter*. In flat space, b is the distance of closest approach to $r = 0$.

Returning to the Schwarzschild metric, in the equation of motion for r above, we see that if $b^2 < 27G^2M^2$ then dr/dt can never be zero, since

U_{max} is always less than $1/b^2$. Thus if the impact parameter is $b < \sqrt{27}GM$ and $dr/dt < 0$ initially (that is, the photon is approaching $r = 0$), then it must continue to approach $r = 0$ forever. The only way it can do this is to spiral in towards the origin.

If $b > \sqrt{27}GM$, there will be two positive values of r for which $U(r) = 1/b^2$ (since this equation is actually a cubic equation in r , there are 3 solutions, but one of them is always negative, which we ignore). The values of r between these solutions make $U > 1/b^2$ which is not allowed, since that would require the first term, which is a square, to be negative. Thus a photon coming in with $dr/dt < 0$ approaches until r is the higher of the two solutions, at which point $dr/dt = 0$. After that, dr/dt becomes positive, and the photon recedes in some other direction.

For example, if $b = 6GM$, the photon will approach until it reaches the larger root, which is $r = 4.453GM$ and then recede to infinity.

If we consider a cylinder of light heading in towards the central mass, then all photons with $b < \sqrt{27}GM$ will be absorbed by the mass, thus all light within a cylinder of radius $R = \sqrt{27}GM$ will be absorbed. Photons with impact parameters outside this value will not be absorbed, but will be deflected by the mass and continue on back out to infinity.

If $b = \sqrt{27}GM$, then there is only one positive value of r for which $U = 1/b^2$, and that is $r = 3GM$. When the photon reaches that radius, it can continue either by spiralling inwards or receding to infinity, or by entering an unstable circular orbit.

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