p.602 Magnetars + Soft Gamma Repeaters

Magnetar = ns w/ $B \sim 10^{11}$ T, P = 5-8 s, may be source of SGRs (soft gamma-ray repeaters).
Correlated w/ young ($\sim 10^4$ yr) SNRs.
Emission mechanism - B-field stresses cause crust to crack, resulting in huge release of energy.

Ch. 17 General Relativity + Black Holes

§17.1 The General Theory of Relativity p.609

Newtonian gravity $F = G\frac{Mm}{r^2}$ worked fine, except for an inconsistency in the perihelion shift of Mercury (Fig 17.1)
Perihelion shifts by 574"/century, 43" more than predicted by Newtonian grav.
GR is a more accurate theory of gravity + predicts it correctly.

The Curvature of Spacetime

Special Relativity (SR) is special in dealing only w/ constant velocity
GR was developed by Einstein in 1907-15
GR is a geometric theory. (F17.2 p.611) Mass curves spacetime + curved spacetime tells mass how to move.
Gravity also bends the path of light (Fig. 17.3 p.611)
Spacetime is curved thru 4th spatial dimension. Light takes shortest path in this curved space time (Fig 17.4 p612)
Dotted line ACB in Fig. 3+4 looks shorter, but is actually longer.
Also, time runs slower at point C - both effects contribute equally to making the solid line the shorter (time) path.
GR has been experimentally verified.
AE himself did the calculations of the perihelion shift of Mercury.
"For a few days, I was beside myself with joyous excitement."
Light-bending was measured by Arthur Eddington in the solar eclipse of 1919. (1.75") (Fig. 17.5 p613)

p.613 The Principle of Equivalence

There are 2 kinds of mass - inertial mass $F = m_i a$ + gravitational mass $F_g = G\frac{Mm_g}{r^2}$.
It is an experimental fact that $m_i = m_g$ to 1 part in 10^{12}, but this is inexplicable in Newtonian mechanics.

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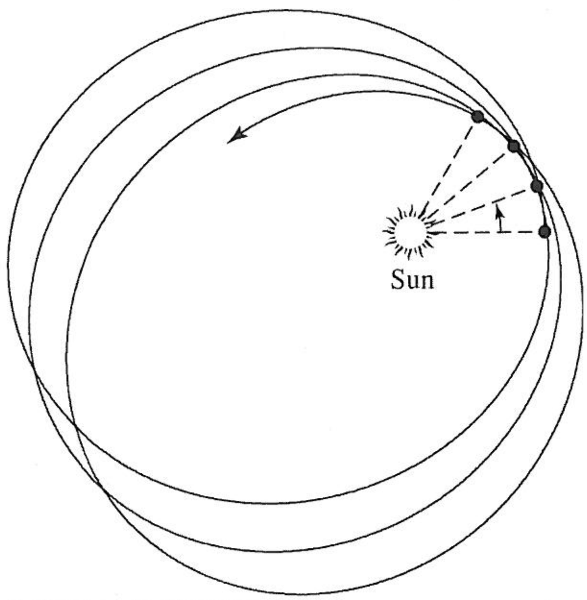

Fig. 17.1 Perihelion shift of Mercury (exaggerated)

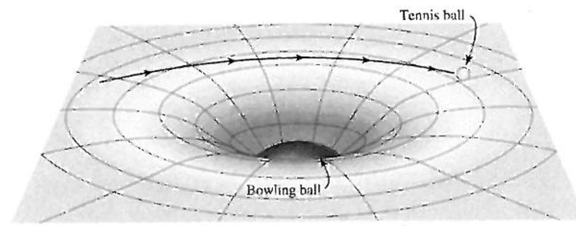

Fig. 17.2 Rubber sheet analogy for curved space around Sun

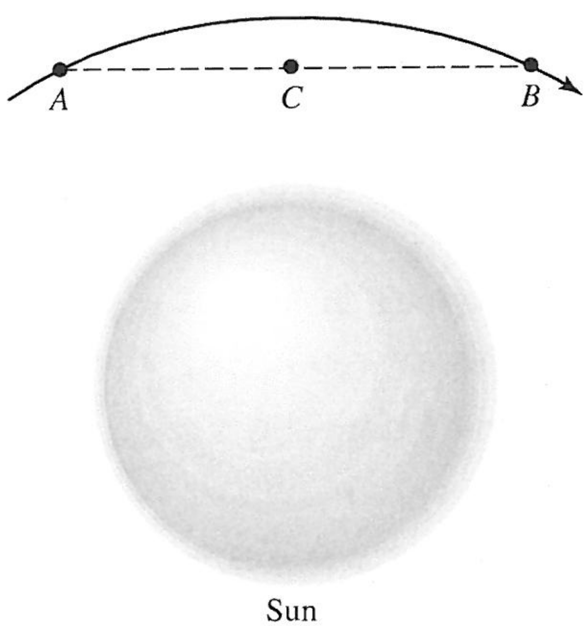

Fig. 17.3 Photon's path around Sun (curvature exaggerated).

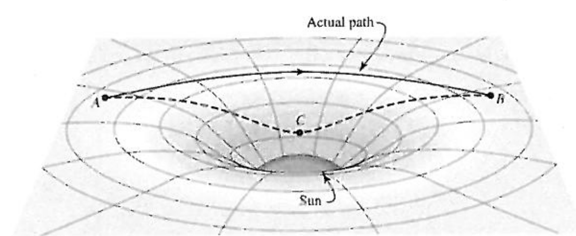

Fig. 17.4 Two photon paths. ACB is the projection of ACB from Fig. 17.3.

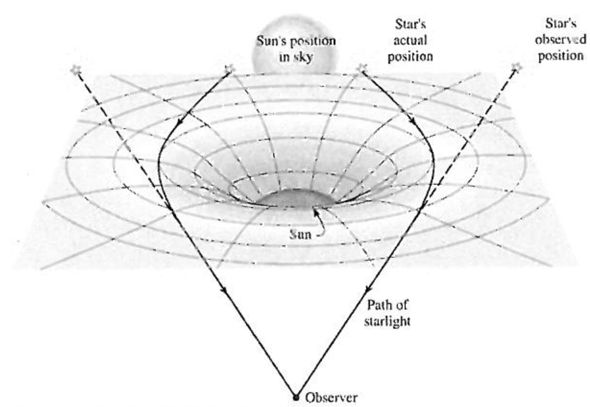

Fig. 17.5 Bending of starlight during solar eclipse.

GR is based on Einstein's "happiest thought" of 1907 "If a person falls freely he does not feel his own weight.

(Fig. 17.6 p.615) Gravity is equivalent to an accelerating laboratory.

(Fig 17.7 p.616)

(Fig. 17.8) Must use local inertial frames, small enough that $\vec{g} \approx$ const. inside.

Principle of Equivalence: All local, freely falling, nonrotating laboratories are fully equivalent for the performance of all physical experiments.

p. 617 The Bending of Light

(Fig 17.9) Photon fired horizontally in freely falling lab – falls distance $d = \frac{1}{2}gt^2 \Rightarrow$ deflection $\angle\phi = \frac{lg}{c^2} = 10^{-15}$ rad for $l = 10$m, (17.10)

p. 619 Gravitational Redshift + Time Dilation

This time let the photon be fired upwards in the freely falling laboratory. (Fig 17.11)

In the falling frame gravity is abolished, so a frequency meter in the ceiling measures the same frequency ν_0.

Ground observer $\Rightarrow$ light traveled time $t = h/c \Rightarrow$ reached speed $gt = \frac{gh}{c}$

$\Rightarrow$ should have experienced blue-shift $\frac{\Delta\nu}{\nu_0} = \frac{v}{c} = \frac{gh}{c^2}$.

But there was no change in frequency $\Rightarrow$ must be another effect.

Gravitational redshift $\frac{\Delta\nu}{\nu_0} = -\frac{gh}{c^2}$

Outside observer observes only the gravitational redshift.

If light travels downwards, it's a blue shift.

Ex. 17.1.1 p. 620 Tested at Harvard in 1960. γ-rays emitted from bottom of 22.6 m tower.

$\Delta\nu/\nu_0 = -gh/c^2 = -9.8\,\text{m/s}^2\, 22.6\,\text{m}/(3\times10^8\,\text{m/s})^2 = -2.46\times10^{-15}$

Experimental result $\Delta\nu/\nu_0 = -(2.57\pm0.26)\times10^{-15}$

For photon traveling outwards to infinity get $\int_{\nu_0}^{\nu_\infty}\frac{d\nu}{\nu} = -\int_{r_0}^{\infty}\frac{g\,dr}{c^2}$

$= -\int_{r_0}^{\infty}\frac{GM}{r^2c^2}dr \Rightarrow \ln\frac{\nu_\infty}{\nu_0} = -\frac{GM}{r_0c^2} \Rightarrow$

$$\frac{\nu_\infty}{\nu_0} = e^{-GM/r_0c^2} \simeq 1 - \frac{GM}{r_0c^2} \quad \left(\frac{GM}{r_0c^2} \ll 1\right)$$

Not exact, because all dr's are in different frames.

Exact $\nu_\infty/\nu_0 = (1 - 2GM/r_0c^2)^{\frac{1}{2}}$

Redshift parameter defined in Ch. 4:

$$z = \frac{\lambda_\infty - \lambda_0}{\lambda_0} = \frac{\nu_0}{\nu_\infty} - 1 = \left(1 - \frac{2GM}{r_0c^2}\right)^{-\frac{1}{2}} - 1 \simeq \frac{GM}{r_0c^2} \quad \left(\text{if } \frac{GM}{r_0c^2} \ll 1\right).$$

Let Δt be the time for a complete oscillation of wave of frequency ν, $\Delta t = 1/\nu$.

$$\frac{\Delta t_0}{\Delta t_\infty} = \frac{\nu_\infty}{\nu_0} = \left(1 - \frac{2GM}{r_0c^2}\right)^{\frac{1}{2}} \simeq 1 - \frac{GM}{r_0c^2} \text{ (weak field)}$$

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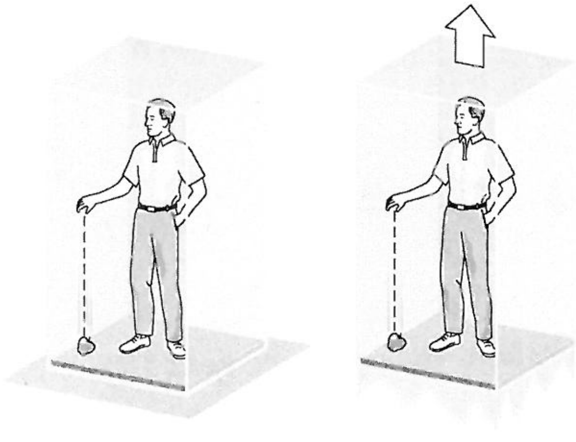
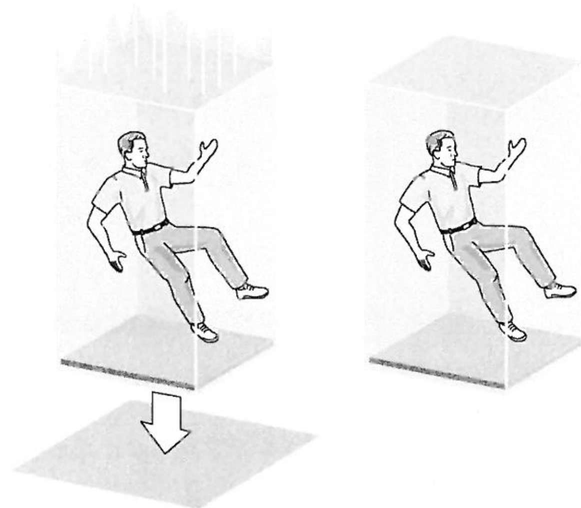


(a) (b)

Fig. 17.6 Gravity is equivalent to accelerating laboratory.



(a) (b)

Fig. 17.7 Gravity abolished in freely falling laboratory.

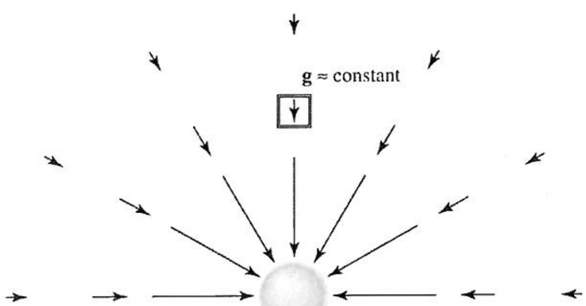
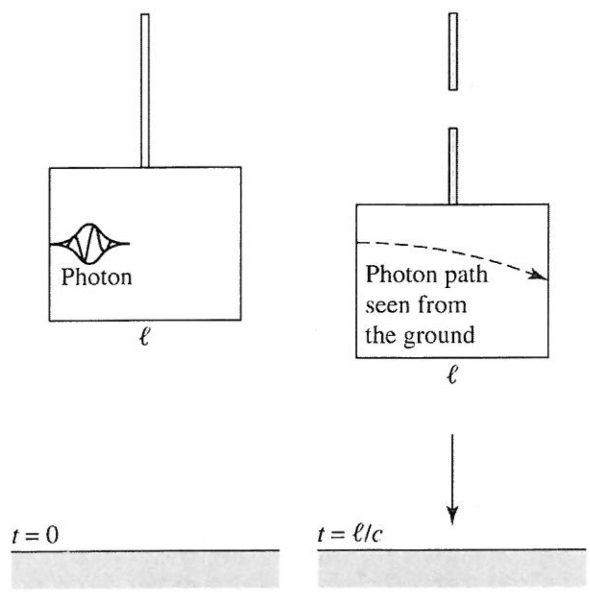


Fig. 17.8 Local inertial frame w/ g ≈ constant inside.



(a) (b)

Fig. 17.9 Equivalence principle for horizontally traveling photon.

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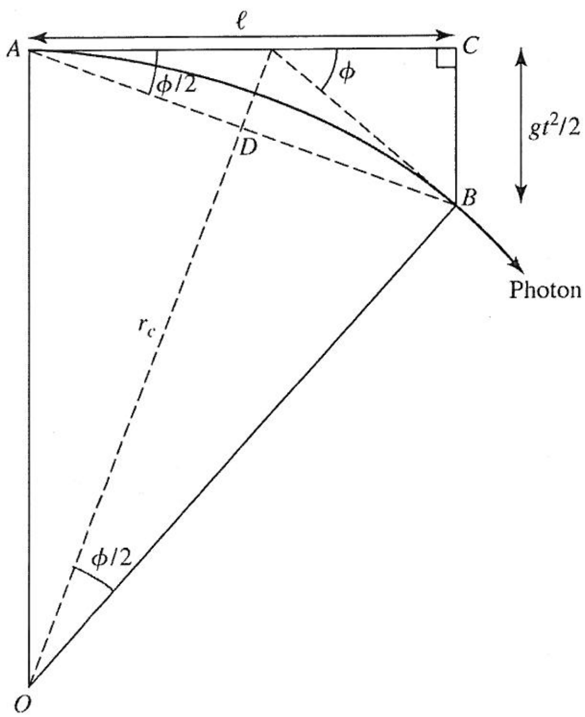

Fig. 17.10 Geometry for radius of curvature r_c & angular deflection ϕ.

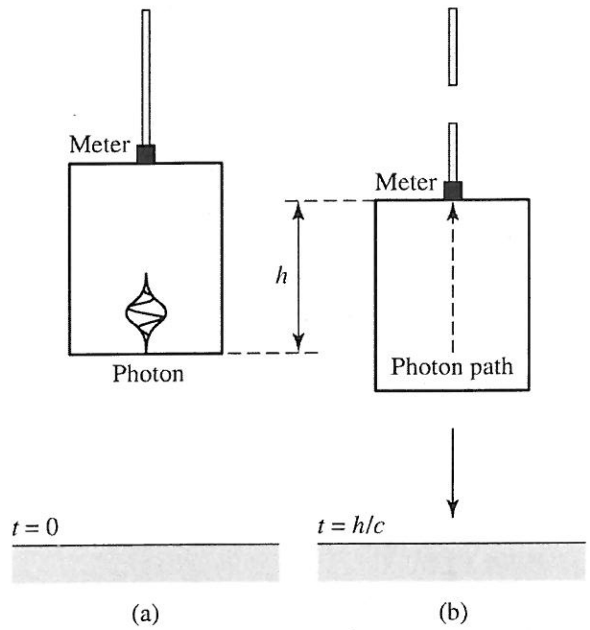

Fig. 17.11 Equivalence principle for vertically traveling photon.

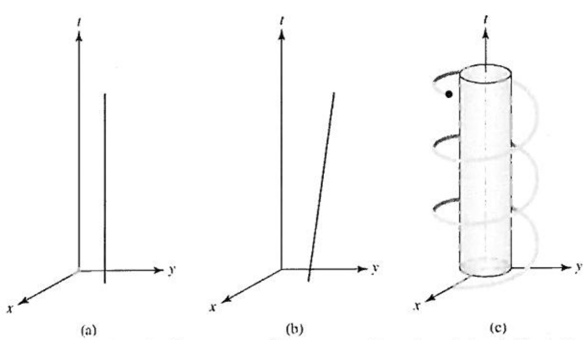

Fig. 17.12 Worldlines for (a) man at rest, (b) woman running w/ constant v, & (c) satellite orbiting Earth.

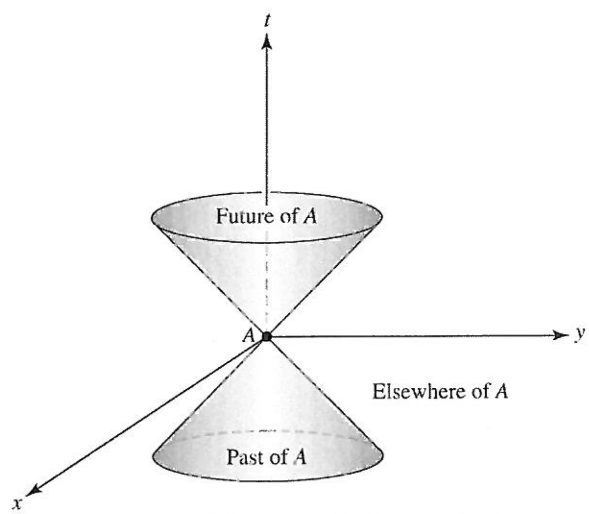

Fig. 17.13 Light cones generated by horizontally traveling photons emitted at $t = 0$.

This is gravitational time dilation - time runs slower in a grav. field.
2 identical clocks side by side, One lowered into grav. well & brought back up - it will be behind.

Ex. 17.1.2 p. 622 Sirius B, $R = 5.5 \times 10^6$ m, $M = 2.1 \times 10^{30}$ kg
$Z \simeq GM/Rc^2 = 2.8 \times 10^{-4}$ (measured $(3.0 \pm 0.5) \times 10^{-4}$)
They also show that a clock on Sirius B loses 1 s per hour.

§17.2 Intervals & Geodesics p 622

Point in spacetime (x, y, z, t) = event
Field equations $\mathcal{G} = -\frac{8\pi G}{c^4} \tilde{T}$
$\tilde{T}$ = 4x4 stress-energy tensor, with components equal to fluxes of mass/energy/momentum in the different directions.
$\mathcal{G}$ = Einstein tensor describes curvature of spacetime via derivatives of metric tensor.
So - curvature of spacetime caused by energy-momentum densities & fluxes.

p.623 Worldlines & World Cones
(Fig. 17.12 p623) Spacetime diagrams (z suppressed) - man sleeping on couch, woman running to a sale, satellite orbiting Earth.
(Fig. 17.13 p624) Event A = flashbulb set off at origin at $t=0$.
Worldlines of photons in xy plane = light cone ($45°$ w/ proper scaling).
Massive particle $v<c \Rightarrow$ inside lightcone = future of A = everything that could be caused by A.
Inside lower light = past of A = set of events that could cause A.
Outside the lightcones = elsewhere of A - region of spacetime completely inaccessible to us. Example: California, right now. We can influence CA in the future, it can influence us in the future, but not now.
Your destiny, your entire future worldline, must lie within your future lightcone.

p 624 Spacetime Intervals, Proper Time, & Proper Distance
In flat 3D space, the distance Δl between 2 points is given by
$(\Delta l)^2 = \Delta x^2 + \Delta y^2 + \Delta z^2 = (x_2-x_1)^2 + (y_2-y_1)^2 + (z_2-z_1)^2$, & is invariant under translation & rotation.
In flat spacetime, the (spacetime) interval Δs is given by
$\Delta s^2 = [c(t_B - t_A)]^2 - (x_B - x_A)^2 - (y_B - y_A)^2 + (z_B - z_A)^2$ = (distance traveled by light in $|t_B - t_A|)^2$ - (distance between events A & B$)^2$, & is invariant under Lorentz transformations.
If $(\Delta s)^2 > 0 \Rightarrow$ timelike $\Rightarrow$ events causally related.

∃ inertial frame which moves from one event to other, so $\Delta X=0$ so proper time interval $\Delta\tau = \frac{\Delta s}{c}$ (proper time measured by clock present at both events). (Fig. 17.14 p. 626)

If $(\Delta s)^2=0$, interval is <u>lightlike</u> or <u>null</u>, $\Delta\tau=0$

If $(\Delta s)^2<0 \Rightarrow$ spacelike $\Rightarrow$ not causally related. Can find frames in which $\Delta t<0$, >0, or $=0$.

Proper distance (length) = (distance between events in frame in which $\Delta t=0$) $= \Delta \mathcal{L} = \sqrt{-(\Delta s)^2}$ in this case.

$(\Delta s)^2 <, =,$ or $>0 \Rightarrow$ event is outside, on, or inside lightcone.

<u>p626 The Metric for Flat Spacetime</u>

Flat 3D space ⇒ differential distance <u>formula = metric</u>: $(d\ell)^2=(dx)^2+(dy)^2+(dz)^2$

Distance along path $P = \Delta\ell = \int_1^2 \sqrt{(d\ell)^2} = \int_1^2 \sqrt{(dx)^2+(dy)^2+(dz)^2}$

Similarly, for flat spacetime, <u>the interval along worldline</u> $\mathcal{W}$ is

$$\Delta s = \int_A^B \sqrt{(ds)^2} = \int_A^B \sqrt{(c\,dt)^2-(dx)^2-(dy)^2-(dz)^2}$$

Proper time along curved worldline $= \Delta s/c$ ($(\Delta s)^2>0$), $=0$ ($(\Delta s)^2=0$), undefined (or imaginary) for $(\Delta s)^2<0$. (= time measured by watch moving along worldline)

Compare Δs for 2 worldlines connecting events A + B, both of which occur at the origin of an inertial frame. (Fig. 17.15 p. 628)

For the straight line $A\to B$, $dx=dy=dz=0$, so

$$\Delta s(A\to B) = \int_A^B \sqrt{(c\,dt)^2-(dx)^2-(dy)^2-(dz)^2} = \int_A^B c\,dt = c(t_B-t_A)$$

On lines AC + CB, $\frac{dx}{dt} = v_{AC}$ + v_{CB} respectively, so $\Delta s(A\to C\to B)$

$$= \int_A^C \sqrt{(c\,dt)^2-(v_{AC}\,dt)^2} + \int_C^B \sqrt{(c\,dt)^2-(v_{CB}\,dt)^2}$$

$$= (t_C-t_A)\sqrt{c^2-v_{AC}^2} + (t_B-t_C)\sqrt{c^2-v_{CB}^2} < c(t_C-t_A)+c(t_B-t_C) = \Delta s(A\to B)$$

In spacetime, a straight line is the <u>longest</u> distance between 2 events.

This represents the <u>twin paradox</u>: AB is the worldline of the Earthbound twin, ACB is the twin who travels to a distant star + then returns.

Each twin measures their proper-time as $\Delta s/c$: Earthbound twin ages more.

<u>p628 Curved Spacetime + the Schwarzschild Metric</u>

"Straightest possible worldline" between events = geodesic.

Flat spacetime: geodesic = straight line. In curved spacetime it is curved.

Paths followed by freely-falling objects are geodesics, + these are maxima, minima, or inflection points (compared to other worldlines connecting the 2 events.

In flat spacetime we have $(ds)^2=(c\,dt)^2-(d\ell)^2=(c\,dt)^2-(dr)^2-(r\,d\theta)^2-(r\sin\theta\,d\phi)^2$

In the vicinity of a spherical mass, this metric is changed.

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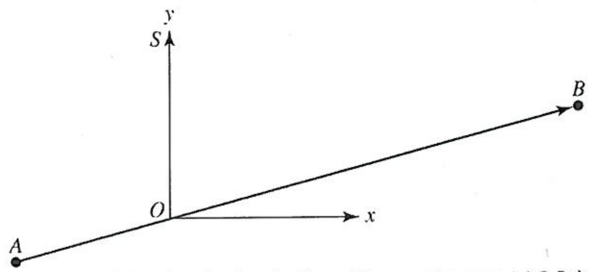

Fig. 17.14 Inertial frame S moving along timelike worldline connecting events A & B. Both events occur at origin of S.

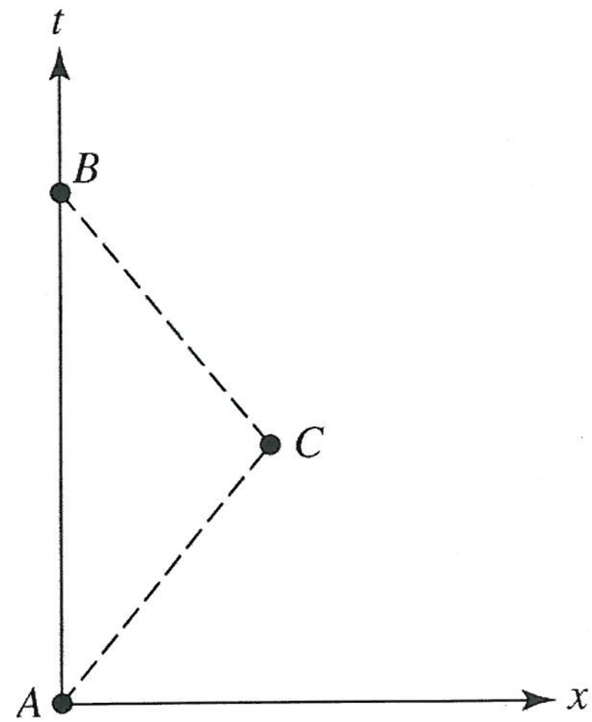

Fig. 17.15 Worldlines connecting events A & B.

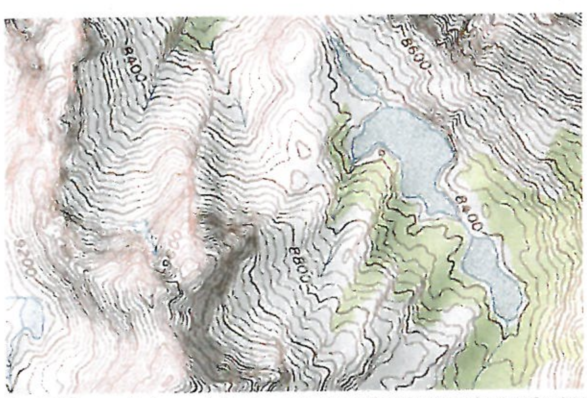

Fig. 17.16 Topographical map w/ elevation contour lines. Shortest distance between 2 points may not be straight line.

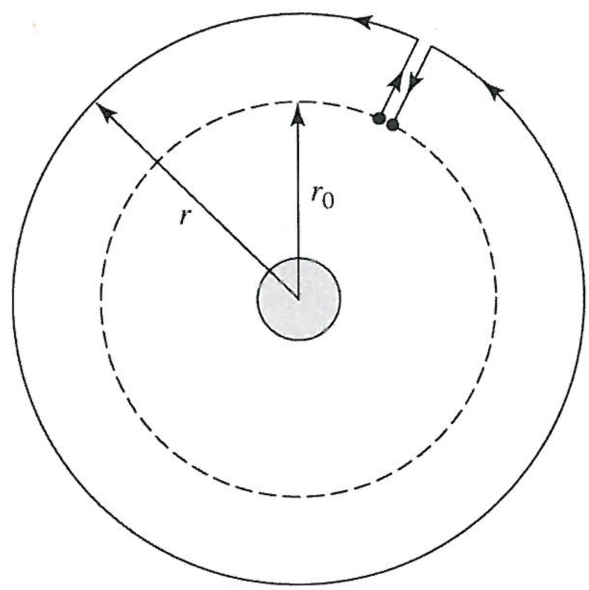

Fig. 17.17 "Orbit" of satellite, showing radial motions used to keep endpoints of worldline fixed. Net effect is circular orbit.

(t, r, θ, ϕ) are coordinates measured by observer far from mass M (at ∞).
There are problems with measuring r from the center of M, so instead use spheres centered at origin, define r by area $= 4\pi r^2$.
Coordinate speed = rate at which spatial coordinates change.
"In 1916, just 2 months after Einstein published his general theory of relativity, the German astronomer Karl Schwarzschild (1873–1916) solved Einstein's field equations to obtain what is now called the Sch. metric".
(He died of a disease developed at the Russian front. He enlisted even though he was >40 yrs old.)

$$(ds)^2 = \left(c\,dt\sqrt{1-2GM/rc^2}\right)^2 - \left(\frac{dr}{\sqrt{1-2GM/rc^2}}\right)^2 - (r\,d\theta)^2 - (r\sin\theta\,d\phi)^2$$

It is valid only outside the spherical mass distribution.
Proper distance measured at same time ($dt=0$) between 2 points w/ $d\theta = d\phi = 0$ is $dL = \sqrt{-(ds)^2} = dr/\sqrt{1-2GM/rc^2} > dr$
Spatial distance $> dr$ (Fig. 17.16 p631) Spatial distance > map distance.
Clock at rest at r measures proper time $d\tau = \frac{ds}{c} = dt\sqrt{1-\frac{2GM}{rc^2}} < dt$.
Time between ticks of clock as measured by observer at ∞ $= dt > d\tau$.
$\Rightarrow$ gravitational time dilation.

p.631 The Orbit of a Satellite

fast! Newtonian: $\frac{v^2}{r} = \frac{GM}{r^2} \Rightarrow v = \sqrt{\frac{GM}{r}}$

Circular orbit above equator: $\theta = 90°$, $dr = d\theta = 0$, $d\phi = \omega\,dt$

$$(ds)^2 = \left[\left(c\sqrt{1-2GM/rc^2}\right)^2 - r^2\omega^2\right]dt^2$$

$$\Delta s\,(1\text{ orbit}) = \int_0^{2\pi/\omega}\sqrt{c^2 - \frac{2GM}{r} - r^2\omega^2}\,dt$$

Variation must have fixed endpoints (r_0), so use this path (Fig. 17.17 p.633) to vary r (radial portions have negligible Δs)

$$\Rightarrow 0 = \frac{d}{dr}\sqrt{c^2 - \frac{2GM}{r} - r^2\omega^2} \Rightarrow 0 = \frac{2GM}{r^2} - 2r\omega^2$$

$$\Rightarrow v = r\omega = \sqrt{\frac{GM}{r}}\ \checkmark$$ geodesic (Fig. 17.18 p634)

This is true even for orbit around black hole.

§17.3 Black Holes p.633

Setting the classical escape velocity $\sqrt{2GM/R}$ to c gives $R = 2GM/c^2$.
Classically, not even light could escape from a star with such a small radius.
The Schwarzschild Radius

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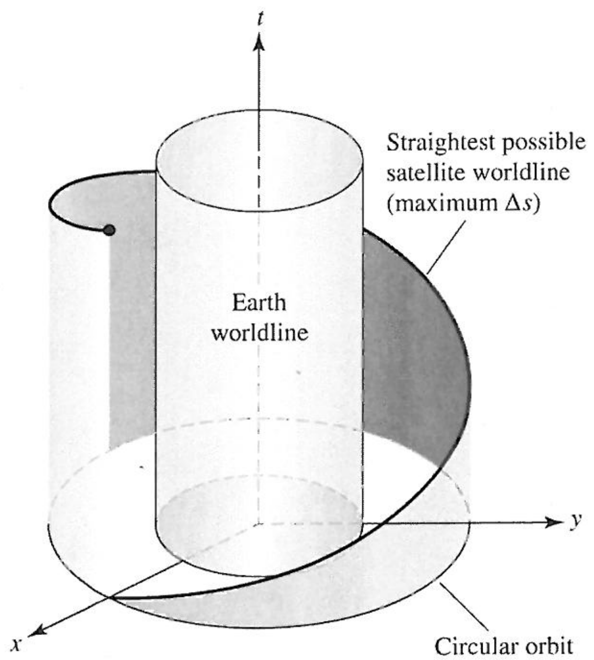

Fig. 17.18 Straightest possible worldline thru curved spacetime & its projection onto orbital plane of satellite.

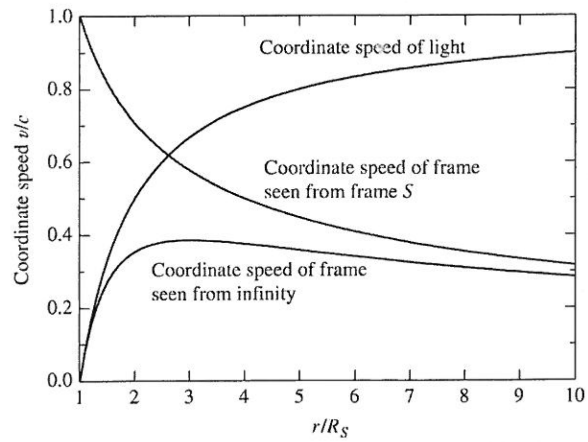

Fig. 17.19

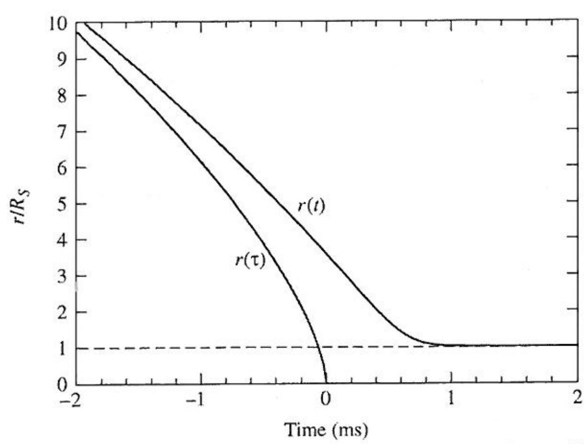

Fig. 17.20 Coordinate r(t) of freely falling frame S according to observer at rest at infinity, & r(τ) according to observer in frame S. (R_S for 10 $M_\odot$ black hole.)

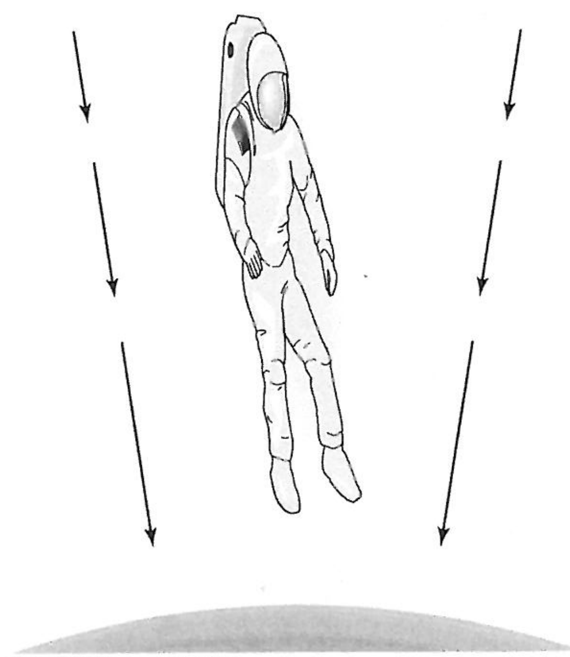

Fig. 17.21 Tidal forces near black hole.

This radius, called the Schwarzschild radius, is also the radius at which the $\sqrt{1-2GM/rc^2}$ terms in the Schwartzschild metric $\to 0$.

$R_S = 2GM/c^2 = 2.95(M/M_\odot)$ km

Lots of strange things happen near $r = R_s$.

Eq. 17.24: $dt = d\tau/\sqrt{1-2GM/rc^2} = d\tau/\sqrt{1-R_s/r}$

$d\tau$ is proper time of clock at r, dt = time measured by distant observer $\to \infty$.

Time is frozen at $r = R_s$! †Fig 17.19 p636

Coordinate speed of light: $ds = d\theta = d\phi = 0 \Rightarrow \frac{dr}{dt} = c\left(1-\frac{2GM}{rc^2}\right) = c\left(1-\frac{R_s}{r}\right) \to 0$

Nothing can be seen from within $r = R_s$ - the event horizon of the black hole.

At the (unobservable) center of a bh is the singularity - a point of infinite density + curvature of spacetime. (QM may smear this out to a size ~ Planck length $l_p = \sqrt{\frac{\hbar G}{c^3}} = 1.6\times10^{-35}$ m.)

Law of Cosmic Censorship: no naked singularities - unclothed - without event horizon.

p636 A Trip into a Black Hole

Time for a photon to travel out from r_1 to $r_2 > r_1$:

fast!

$\Delta t = \int_{r_1}^{r_2} \frac{dr}{dr/dt} = \int_{r_1}^{r_2} \frac{dr}{c(1-R_s/r)} = \int_{r_1}^{r_2} \frac{r\,dr}{c(r-R_s)} = \int_{r_1}^{r_2} \frac{r-R_s+R_s}{c}\frac{dr}{r-R_s} = \int_{r_1}^{r_2}\left(\frac{1}{c} + \frac{R_s}{c(r-R_s)}\right)dr$

$= \left[\frac{r}{c} + \frac{R_s}{c}\ln(r-R_s)\right]\Big|_{r_1}^{r_2} = \frac{r_2-r_1}{c} + \frac{R_s}{c}\ln\left(\frac{r_2-R_s}{r_1-R_s}\right)$. For $r_1 = R_s$, $\Delta t = \infty$.

This is true for a photon coming out from $r_1 = R_s$ or inwards from $r_1 = \infty$.

So a bh is a frozen star - even the surface of the star that formed it appear to be at the event horizon.

What if an astronaut decided to free-fall into a 10 $M_\odot$ ($R_s = 30$ km) bh?

Observer at ∞ sees her slowing down as she approaches R_s, her motions become slow, she emits fewer + fewer photons, which are more + more redshifted.

(Fig 17.20 p637)

From her perspective, tidal forces stretch her in the radial direction + squeeze her laterally. (Fig. 17.21 p638)

She falls through the event horizon + is crushed in the singularity $\Delta\tau = 6.6\times10^{-5}$ s

It is impossible to be at rest at $r < R_s$: $dr = d\theta = d\phi = 0 \Rightarrow$

$(ds)^2 = (c\,dt)^2\left(1-\frac{R_s}{r}\right) < 0$ (spacelike interval, not permitted for particles)

p. 639 Mass Ranges of Black Holes

Stellar-mass bhs: $M = 3-15\ M_\odot$ (core collapse of supergiant star)

Intermediate-mass bhs: IMBHs: $M = 100 \to 1000$ or $10^4\ M_\odot$ (maybe from merger of stellar-mass bh's)

Supermassive bhs (SMBHs) exist at centers of most galaxies: $10^5 - 10^9\ M_\odot$ (MW BH $= 3.7\pm0.2\times10^6\ M_\odot$). Formation model still unclear.

(2015 GravWav - $M = 29 + 36\ M_\odot$ bh merger)

Primordial BH's formed in BB, 10^{-8} kg $- 10^5\ M_\odot$

Ex. 17.3.1 R_s (Earth) $= 0.009$ m $= 9$ mm

p640 BHs Have No Hair!

Any irregularities in shape of BH quickly radiated away as grav. waves.

BH can be completely described by M, L, + Q

$L_{max} = \frac{GM^2}{c}$ for bh: $L > L_{max} \Rightarrow$ naked singularity.

__Ex. 17.3.2__ For sun, $L_{max,\odot} = GM_\odot^2/c = 8.81 \times 10^{41}$ kg m² s⁻¹

$L_\odot = 1.63 \times 10^{41}$ kg m² s⁻¹ $= 0.18\ L_{max,\odot} \Rightarrow L \approx L_{max}$ should be common for stellar-mass bh's.

__p 640 Spacetime Frame Dragging__

BH w/ $L \neq 0$ not spherically symmetric $\Rightarrow$ described by Kerr (Roy Kerr, 1963) metric, not Schwarzschild. (why do my arms move outward when I rotate?)

Rotating bh (or other object) induces rotation in surrounding spacetime $\Rightarrow$ frame dragging: an inertial frame rotates.

(Fig. 17.22 p. 641) In __ergosphere__ all particles must move in same direction as bh rotation. Outer limit of ergosphere = static limit $\Rightarrow$ particles can stand still.

fun! __p. 642 - Tunnels in Spacetime__ (Fig. 17.23 p. 642)

Einstein-Rosen bridges + wormholes connecting 2 distant parts of spacetime are theoretically possible but require exotic unknown matter-energy to keep them open + stable.

Also, wormholes may be impossible (Stephen Hawking says) because they would allow time travel to the past.

fun! __p 643 Stellar-Mass BH Candidates__

The best chance of observing stellar-mass bh's is when they are accreting matter from a normal binary companion. (Fig 17.24 p. 644)

Normal companion evolves, expands, overflows its Roche lobe, forms accretion disk, gas is compressed + heated to millions of K, emits X-rays.

Most of these binary X-ray sources are ns's, but if $M \gtrsim 3 M_\odot$, it's a BH.

1st candidate = Cygnus X-1. Also LMC X-3,

A0620-00: $M \gtrsim 3.82 \pm 0.24\ M_\odot$

V404 Cygni: $M = 12 \pm 2\ M_\odot$

__p. 644 Hawking Radiation__

Stephen Hawking (1974): BH's evaporate.

Virtual particle-antiparticle pair created just outside event horizon, one falls in before they can recombine, so a particle is emitted + the BH's mass decreases. (Fig. 17.25 p. 645)

It is as if a BH emits thermal radiation with $T \propto \frac{1}{M}$, emission rate $\propto R^2 T^4 \propto M^2 M^{-4} \propto M^{-2}$

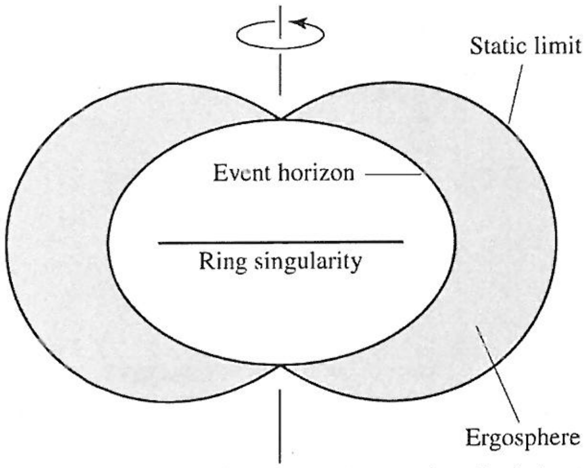

Fig. 17.22Maximally rotating black hole, w/ ring singularity seen edge-on. Event horizon at equator is r = ½Rs.

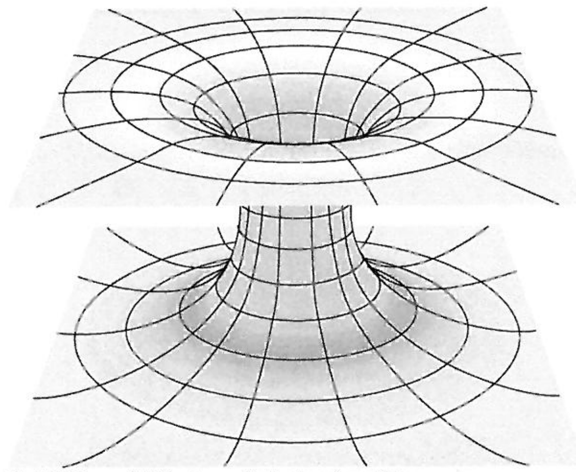

Fig. 17.23 Schwarzschild throat connecting 2 regions of spacetime.

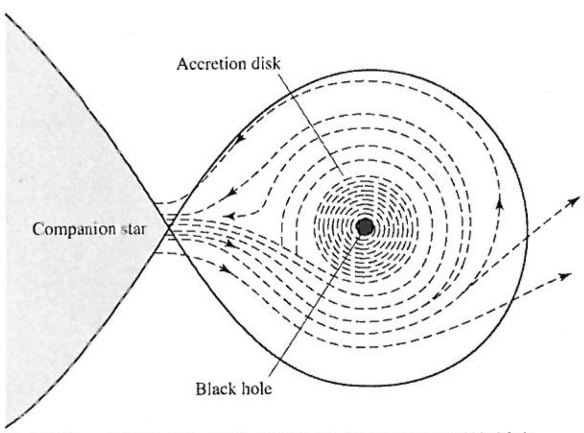

Fig. 17.24 Gas pulled from companion star forms X-ray emitting disk around black hole.

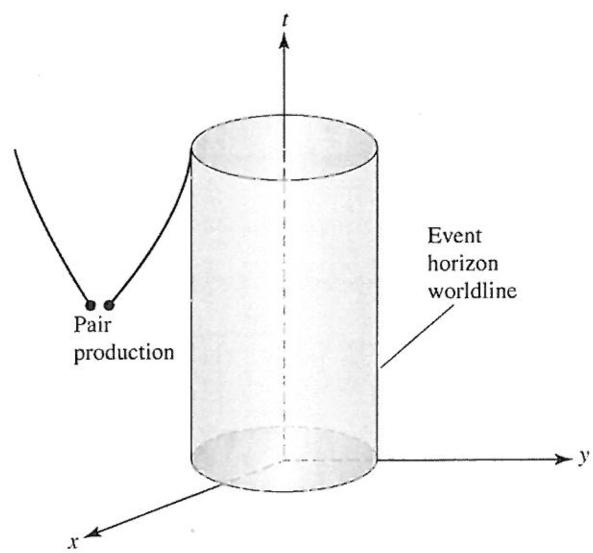

Fig. 17.25 Particle-antiparticle pairs created near event horizon of black hole.

40C

2/18/18

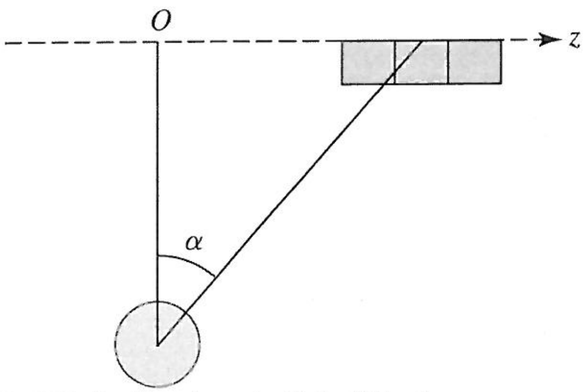

Fig. 17.26 Local inertial frames for measuring deflection of light near Sun.

Evaporation time $\propto M/\text{rate} \propto M^3$

$t_{evap} = 2560\pi^2 \left(\frac{2GM}{c^2}\right)^2 \left(\frac{M}{\hbar}\right) \approx 2\times10^{67} \left(\frac{M}{M_\odot}\right)^3$ yr

Age of universe ~ 13.7 billion years.

Primordial BH w/ $M \sim 1.7\times10^{11}$ kg should evaporate ~ now.

Final evaporation is explosive, releasing ~100 MeV γ's at 10^{13} K, also other particles.

Non-detection ⇒ < 200 BHs w/ this mass per cubic light year.

Ch. 18 Close Binary Star Systems - p653

§18.6 NSs + BHs in Binaries p689

If star in close binary undergoes SN, result may be ns or bh in binary.

In semidetached system (Fig. 18.4), hot gas flows through inner Lagrangian point from companion star onto compact object.

Gravitational energy → X-rays.

It is also possible to have 2 compact objects in binary system.

Formation of Binaries with Neutron Stars or Black Holes

Binary system survives SN of one star if ejected mass small enough.

Simple model: stars in circular orbits, spherically symmetric SN.

Can show (Prob. 18.17) that the system will be unbound ($E_f \geq 0$) if the remnant mass satisfies $\frac{M_R}{M_1+M_2} \leq \frac{1}{(2+M_2/M_1)(1+M_2/M_1)} < \frac{1}{2}$

(Star 1 explodes)

p.690 Capturing Isolated Neutron Stars

In order for a ns to form a binary in an encounter w/ another star, energy must be dissipated.

Passing ns raises tidal bulges on nearly normal star ⇒ tidal capture.

Most effective in region densely populated w/ stars - globular cluster.

In fact, there are lots of X-ray sources in globular clusters.

Or a ns can be captured by a system containing ≥ 2 stars - one is ejected, removing energy from the system.

p.691 - Binary X-ray Pulsars

1st discovered extrasolar X-ray source = Sco X-1 = binary X-ray pulsar.

Atmosphere opaque to X-rays, so must use balloon, rocket, or satellite.

Grav. energy ~ $0.2\,mc^2$ ($\gg E_{nuc}$)

$L_X \approx L_{Ed} \sim 10^{31}$ W, $T \sim 2\times10^7$ K ($\lambda_{max} \sim 0.15$ nm → X-rays)