Jets

Relativistic Astrophysics and Cosmology: Lecture 11

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Monday 30$^{\text{th}}$ October 2023

Pre-lecture question:

What causes the most luminous events in the universe?

Housekeeping

- Note that the first deadlines for most PhD students are on 5$^{\text{th}}$ December (e.g. the Cavendish trust funding deadlines)
  `https://postgraduate.study.cam.ac.uk/application-process/how-do-i-apply`
- For Astro in Cambridge there are three departments you can apply to:
  - Cavendish Laboratory Astrophysics
    `https://astro.phy.cam.ac.uk/gradresearch`
  - Institute of Astronomy
    `https://ast.cam.ac.uk/admissions`
  - Department for Applied Mathematics and Theoretical Physics
    `https://maths.cam.ac.uk/postgrad/damtp-phd-opportunities`
- These all have slightly different applications procedures, but you can apply to all three if you wish.

Last time

- Active galactic nuclei as supermassive black holes with accretion disks
- AGN feedback with host galaxy

This lecture

- Jets
- Superluminal apparent motion
- Gamma-ray bursts

Next lecture

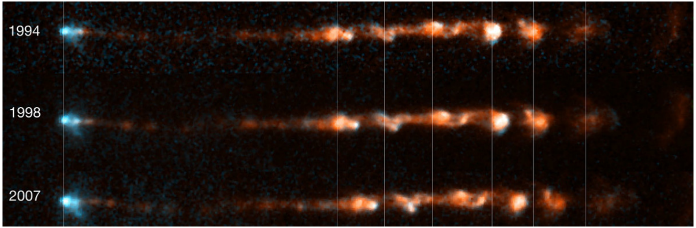
- Neutron stars and pulsars

Jets and radio sources

- A distinctive feature of AGNs is that they often involve not just thermal radiation from hot gas, but also material in more exotic forms – magnetic fields and relativistic electrons which emit synchrotron radiation.
- This is channelled into jets, ejected from the centre at close to the speed of light.
- These radio loud objects are about 10% of all AGN and generally occur in elliptical galaxies – radio-quiet objects are generally in spiral hosts.
- Such phenomena can also be seen in a very wide variety of sizes and scales in astrophysics, so are clearly a generic feature of collapsing matter.

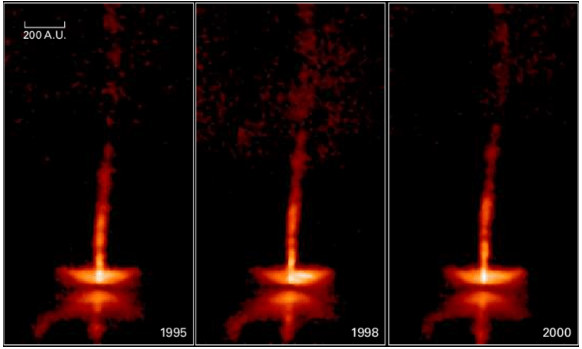
Jets from stars

- Jets are not exclusively seen in AGN; they occur in young stars, where disc accretion is taking place and in accreting white dwarfs, neutron stars and stellar mass black holes.
- The velocity of the jet appears to be similar to the escape velocity of the central object (i.e. relativistic for black holes and neutron stars).



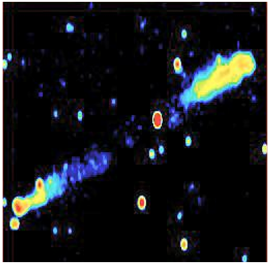
Star forming jets

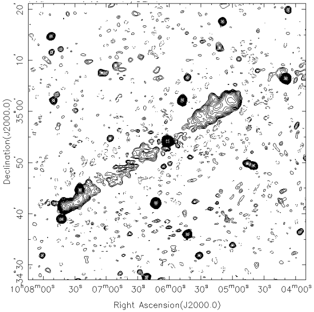
- Images of a stellar nursery taken by HST. Below is a time-lapse of "Head" of nebula on the right.
- Not improbable that our primordial solar system had a similar jet.

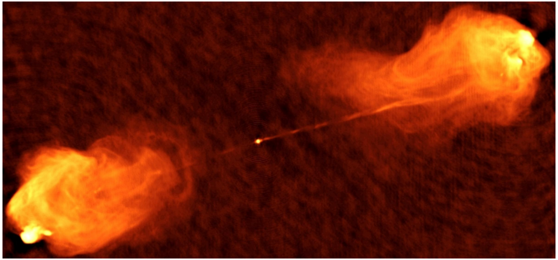


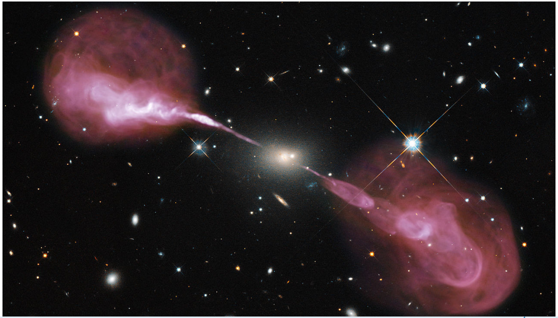
Jets from giant radio galaxies

- These are object more than 2 Mega-parsecs across (6.5 mly, 62× milky way).
- Indicate that these are extremely stable energetic phenomena, maintaining direction and power on megayear timescales.









- M87 has been observed across the electromagnetic spectrum.
- Supergiant galaxy with clear jet visible across the electromagnetic spectrum.
- Jet extends 5000 light years in length.

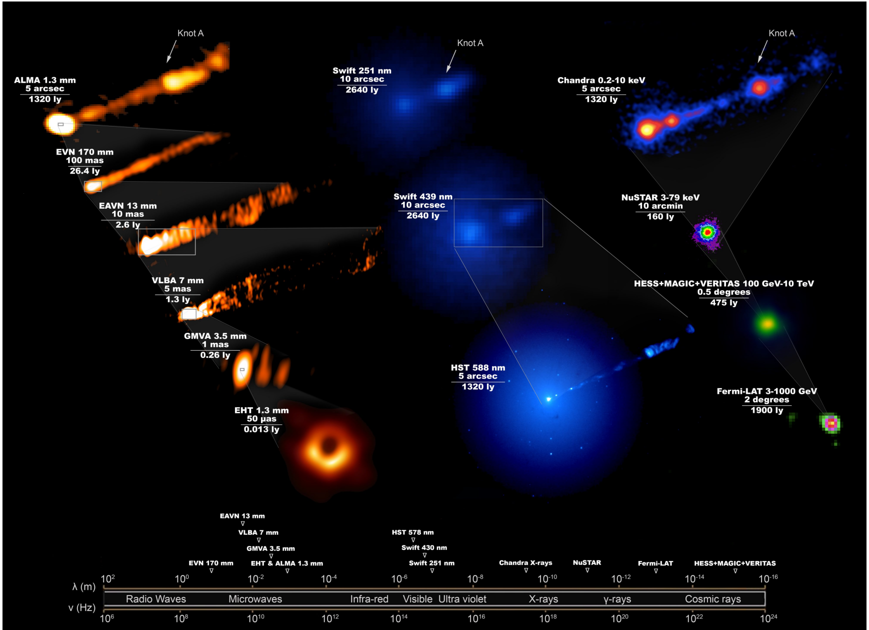
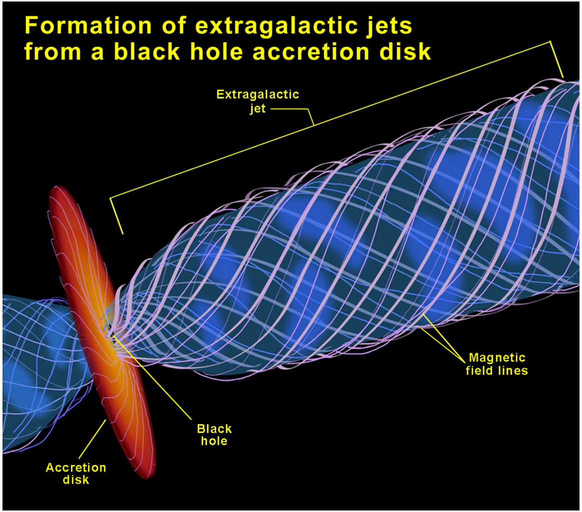


Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

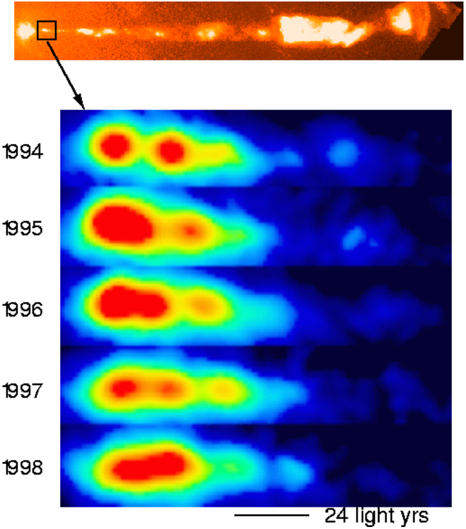
How do jets work?

- Not clear exactly how the jets are produced!
- However, it is generally considered that Jets are due to magnetic fields coiled up by the disc, i.e. they are a magnetohydrodynamic phenomenon.
- In some cases, the jets penetrate to very great distances (larger even than the entire host galaxy), to create an extended radio source. The largest of these is several Mpc across (up to 10 million light years!).



Superluminal motion in Jets

- Blobs in M87 as observed by Hubble appear to be moving at superluminal velocities.
- Placing a ruler over the images gives $v \sim 6c$.
- More remarkably, this is not even unusual!
- Most jets appear to have this property.



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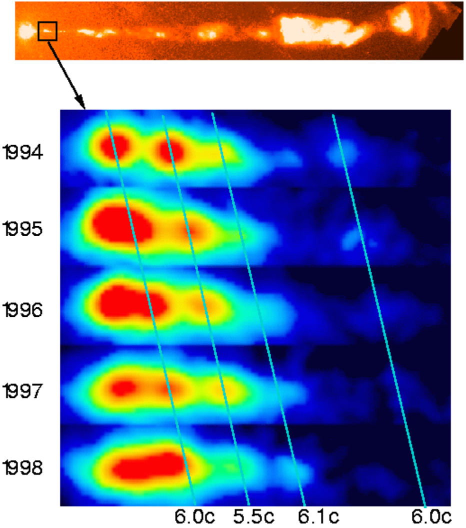
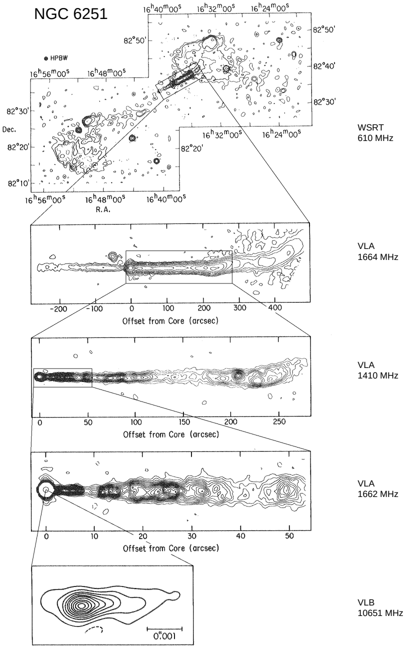
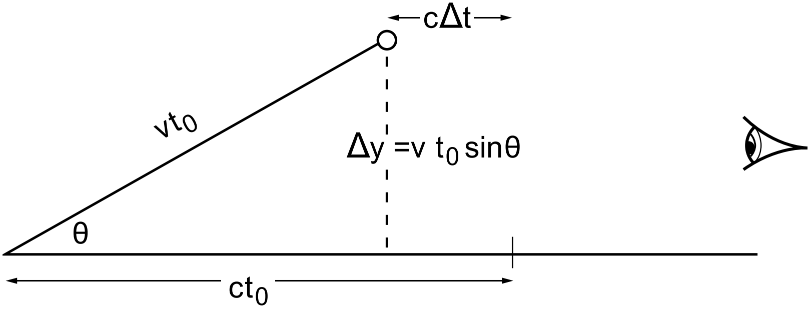


- Motions of this kind have been discovered in many radio quasars, using the technique of Very Long Baseline Interferometry (VLBI).
- This technique allows angular resolutions of much better than a milli-arcsecond to be achieved, corresponding to only tens of lightyears even at the Hubble distance.
- Shown on the right are observations of the giant radio source at NGC6251 on various scales.
- Such measurements unambiguously confirm superluminal motion of objects, and not e.g. some kind of superluminal group-velocity of a wave/optical illusion.



Explanation for apparent superluminal motion



This apparent superluminal motion occurs from geometry because

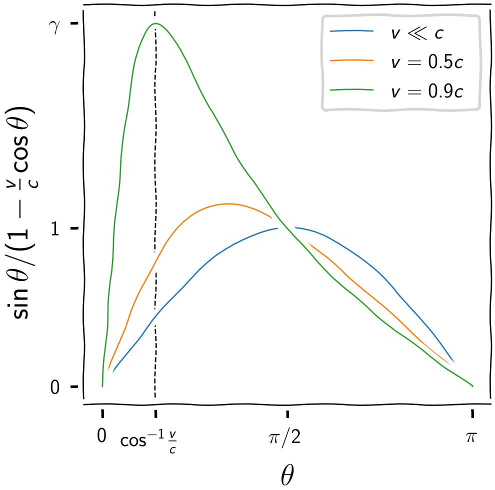
1. The objects have velocity $v \sim c$,
2. The jet is aimed almost directly at us, and
3. We perceive only the transverse velocity.

- Suppose that, at a time zero a blob leaves the centre of a distant galaxy.
- Then after time t_0 the blob will have moved a transverse distance $\Delta y = v t_0 \sin\theta$.
- However, the corresponding time in the observer's frame is $\Delta t = t_0 \left(1 - \frac{v}{c}\cos\theta\right)$.

- The apparent transverse speed is therefore

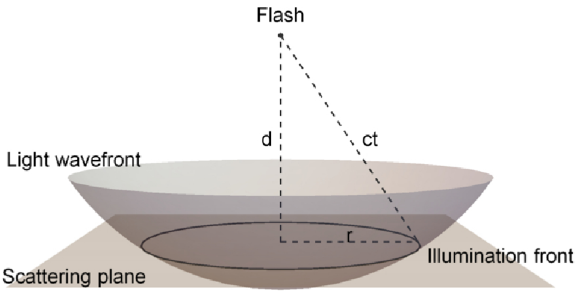
$$\boxed{\frac{\Delta y}{\Delta t} = \frac{v \sin\theta}{1 - \frac{v}{c}\cos\theta}.}$$

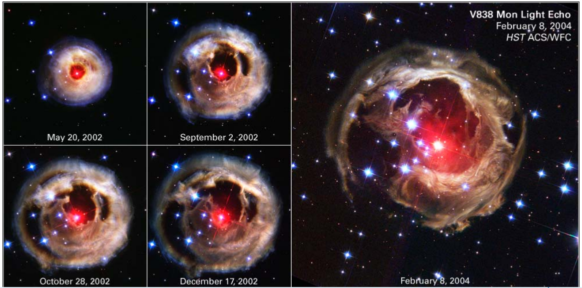
- So a blob moving at $v \sim c$ at an angle where $\theta = \cos^{-1}\frac{v}{c}$ (i.e. $\sin\theta = \gamma^{-1}$) can have an apparent transverse speed $\boxed{\gamma v}$.
- For example, if $\gamma = 10$, and the blobs are moving at $\theta = 6^\circ = 0.1$rad to the line of sight, the apparent transverse speed would be almost $10c$.
- This therefore only occurs due to the finite speed of light and the sharp-angled matter "catching up" with previous emissions.
- Note that the γ is a geometrical coincidence (and nothing to do with special relativity).



Does this break special relativity?

- No.
- Such processes cannot transmit information faster than c, and are analogous to:
  - The intersection of very large scissor blades,
  - A laser pointer on the moon,
  - The illumination front of a torch on a wall.
- Intriguingly this last one is also relevant for supernovae expansion fronts, which appear superluminal.
- The whole sky is full of reflections and rings of light echoes.
- Can collect spectra from long-dead supernovae that occurred hundreds of years ago from shockwave rings that appear now.





Why are these so common?

- Extreme superluminal motions are only expected if the jet is almost pointing at us (to within an angle $\sin\theta \approx \theta \sim \gamma^{-1}$).
- Observations indicate that most jets are pointing nearly directly at us!
- This appears to violate the cosmological principle, with "fingers of God" pointing at Earth.
- However, this is a selection effect, in that jets that are not pointing toward us are in most cases not bright enough to be seen.
- It is therefore not surprising that a substantial fraction of known radio quasars should display superluminal motions.
- This selection effect is substantially enhanced by Doppler boosting and beaming…

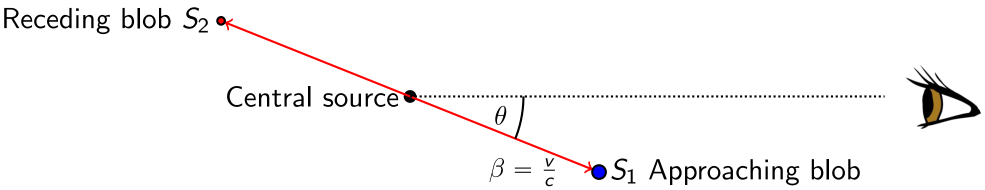
Doppler boosting and beaming of jets

- If a moving blob emits radiation with a spectrum $P(\nu) \propto \nu^{-\alpha}$, the observed intensity at ν scales as $\boxed{D^{3+\alpha}}$, where

$$\boxed{D = \frac{1}{\gamma\left(1 - \frac{v}{c}\cos\theta\right)}}$$

  is the Doppler shift. (N.B: $\alpha \sim 0.5$ usually)
- Two powers of D are due to aberration changing the solid angle, one power is due to the compression of time and the final α factor to the energy shift.
- The occupation number of photons n is phase space (d^3xd^3p) is countable and so Lorentz invariant. The spectral intensity $I_\nu \propto n\nu^3$, so I_ν/ν^3 is also Lorentz invariant.
- Since the Doppler boosted sources (which are precisely the ones oriented in the way required for superluminal effects) appear much more intense, superluminal effects can therefore occur in a large fraction of a radio source sample selected from any survey that is complete down to a given apparent radio intensity.

Beaming and 'unified models' of AGNs

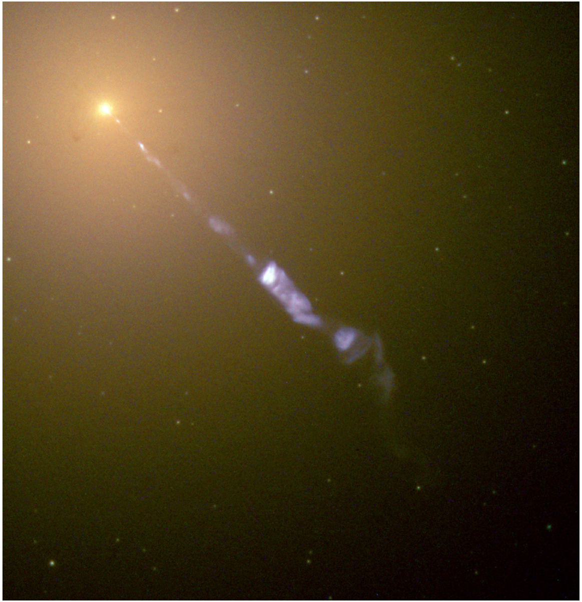


- The flux ratio of two identical anti-parallel jets of velocity $\beta = v/c$ making angles of θ and $\pi - \theta$ to the line of sight is

$$\frac{S_1}{S_2} = \left(\frac{1 + \beta \cos \theta}{1 - \beta \cos \theta}\right)^{3+\alpha},$$

  which for $\theta \ll 1$ but γ large enough that $\gamma\theta \gg 1$, is roughly $(2/\theta)^{6+2\alpha}$ – can be very large.
- This leads astronomers to propose "unified models" of AGN, where the differing classes of AGN we've categorised are actually intrinsically very similar, but appear different due to these viewer-based effects.

- The observed one-sidedness of jets in double radio sources is then a consequence of Doppler favouritism rather than intrinsic asymmetry — the approaching side would be much stronger than the receding side.
- Some astronomers have proposed more elaborate unified models, where there is bright optical emission directed along jet. The well-known jet in the elliptical galaxy M87 would look very bright if the jet were pointing towards us.
- Objects known as BL Lacs are thought to be in this class. Intense gamma-ray blazars are an extreme example of looking down a jet.

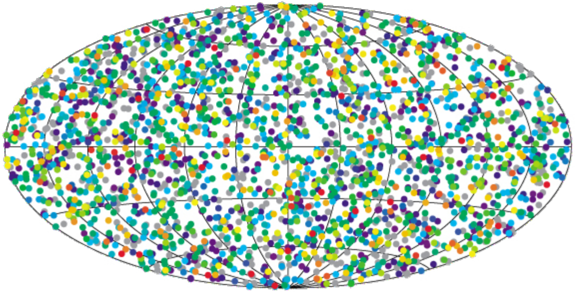


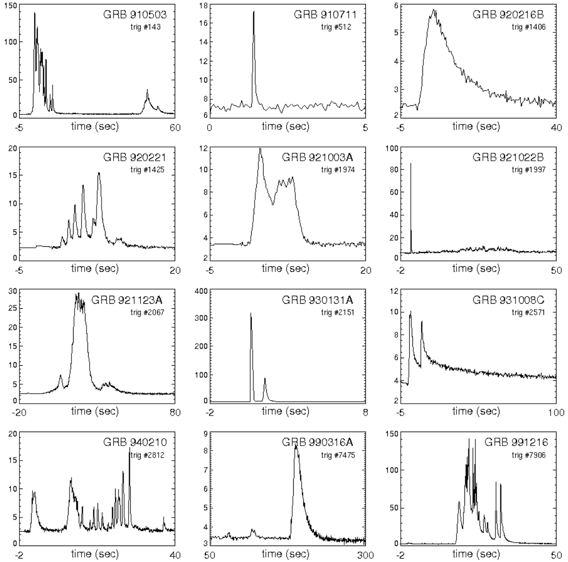
Gamma-ray Bursts

- Sharp bright flashes of gamma-rays were first reported in 1973 from the Vela satellites intended to monitor a ban on nuclear tests in space during the cold war.
- They can be very bright (energy flux as bright as Venus appears in the visible band – one exceptional burst in 2004 had the same flux as the Moon!) and short (less than one second to a few minutes). Several occur per day.
- For many years they were believed to be some Galactic phenomenon associated with neutron stars, but after the Compton Gamma-Ray Observatory found them to be isotropic an extragalactic origin was sought.
- Instruments on BeppoSAX enabled the positions of some bursts to be localised in 1995. They were then optically identified and found to be in distant galaxies. The most distant one has recently been found in a galaxy at z=8.2.
- Given this distance, at face value their brightness is truly terrifying! These are astronomical objects from across the universe which saturate gamma ray detectors (originally designed for measuring local nuclear tests), and for which ionospheric effects are regularly felt (c.f. real "astrology").

Compactness

- An initial challenge in understanding what GRB are stems from their implied compactness.
- Timescales of milliseconds means they need to be less than a millilightsecond across.



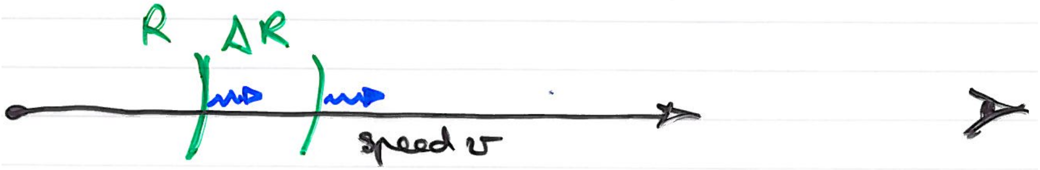


- We discussed compactness in Lecture 8, as a term used to describe the optical depth due to photons in a source $\tau_{\gamma\gamma}$ and scales as L/R.
- It is important when gamma-rays are observed since it determines whether photon-photon collisions can generate electron-positron pairs.
- Let a GRB at distance d have flux F over time δt.
- Now $\tau_{\gamma\gamma} \approx n_\gamma \sigma_\mathrm{T} \delta R$. The source size $\delta R \sim c\delta t$, $n_\gamma = \frac{L}{4\pi\delta R^2\, c\, 2m_e c^2}$, $F = \frac{L}{4\pi d^2}$ and if f of the energy is in photons above the pair production energy $m_e c^2$ then

$$\boxed{\tau_{\gamma\gamma} \approx 10^{15} f \left(\frac{F\delta t}{10^{-9}\,\mathrm{Jm}^{-2}}\right)\left(\frac{d}{3\,\mathrm{Gpc}}\right)^2\left(\frac{\delta t}{10\,\mathrm{ms}}\right)^{-2}.}$$

- Given the typical F, δt and d, their intensity is such that whatever causes them should be swallowed by pair instability since $\tau_{\gamma\gamma} \gg 1$.
- We do see them because GRB sources are expanding relativistically in the form of jets.
- This introduces scaling factors going as the Doppler parameter or, since they are in general beamed towards us, the Lorentz factor γ.

Variability of a relativistic jet: length contraction

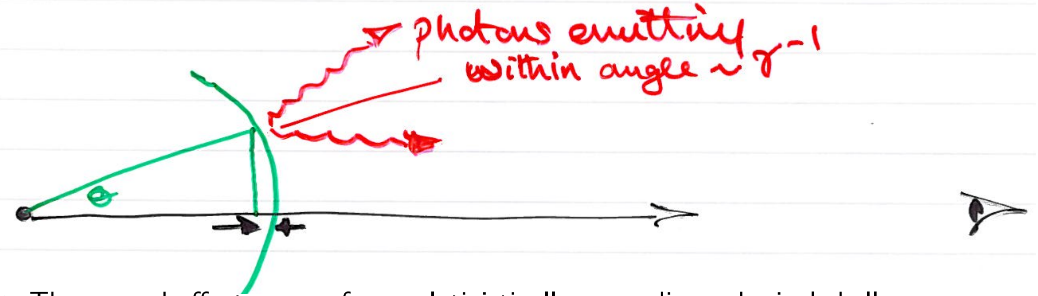


- Special relativity affects how variations in jet emission appear to the observer along the jet direction.
- The first effect is due to the matter "chasing" the photons. Consider that a jet of speed v is pointed direct at us and photons are released when the emission region is at radius R and then $R + \Delta R$.
- The photons are observed with a time difference (expanding in large γ)

$$\Delta t = \frac{\Delta R}{v} - \frac{\Delta R}{c} \approx \frac{\Delta R}{2c\gamma^2} \qquad \left(\frac{v}{c} = \sqrt{1 - \gamma^{-2}} \quad = 1 - \frac{1}{2}\gamma^{-2} + \mathcal{O}(\gamma^{-4}) \right).$$

- This means that an intrinsic fluctuation in the emitter frame is observed to last γ^2 times shorter, or 10 s is compressed to 1 ms if $\gamma \sim 100$.

Variability of a relativistic jet: beaming



- The second effect occurs for a relativistically expanding spherical shell.
- Emission from the shell at an angle θ to the line of sight is delayed relative to the radiation which travels directly from the nearest point by $R(1-\cos\theta)/c$.
- For small angles this is $R\theta^2/2c$.
- Aberration of the emitted radiation means that it is contained with an angle $\sim 1/\gamma$ so we only see emission from angles up to $\theta \sim 1/\gamma$ and the delay is again at most $\Delta t \approx R/2c\gamma^2$.
- This can mean that a burst which is observed to last just 100s can in the comoving frame last 10^6s or over a week.

Variability of a relativistic jet: time dilation

- In terms of photon energies observed in our frame, pair production requires

$$\frac{\epsilon_1 \epsilon_2}{(\gamma m_e c^2)^2} > 2,$$

so the number density above the pair production threshold scales as $\gamma^{-2(\alpha-1)}$, where $P(E) \sim E^{-\alpha}$ and $\alpha \sim 2$

- Putting this all together means that $\tau_{\gamma\gamma} \propto \gamma^6$.
- Then in order that $\tau_{\gamma\gamma} < 1$ we require that $\gamma > 100$.
- GRB are therefore a highly relativistic phenomenon requiring the largest bulk Lorentz factors known.

So what causes gamma ray bursts?

- Analysis of X-ray afterglows combined with γ as above shows that the energy released is typically $\sim 10^{44}$ J similar to that kinetic energy produced by a supernova and about 1% of the binding energy of a neutron star.
- This energy scale suggests that black-hole formation is causing these events e.g. in NS-NS mergers (short bursts), or supernovae core collapse (long bursts).
- Short GRB are found to be associated with lower redshift elliptical galaxies are caused by the merger of neutron star binaries (e.g. GW170817).
- Long bursts originate at the endpoint in the life of some massive stars. The core collapses to form a spinning black hole surrounded by an orbiting torus of matter which accretes rapidly and forms powerful $\gamma > 100$ jets.
- These burrow up the spin axis and create a GRB on emerging from the star. The GRB rate, corrected for the beaming effect, corresponds to about one GRB per 100,000 yr per star-forming galaxy (consistent with the several per day we see).
- Long GRB may be used to trace the cosmic star formation history and out to $z > 10$.
- Galactic gamma ray bursts are hypothesised to explain mass-extinctions on Earth.

Summary

- Jets have an apparent transverse speed which is usually superluminal.

$$\boxed{\frac{\Delta y}{\Delta t} = \frac{v \sin\theta}{1 - \frac{v}{c}\cos\theta} \qquad = \gamma v \quad \text{if } \theta \sim \sin\theta = \gamma^{-1}.}$$

- Jets are usually pointing toward us due to Doppler boosting of $\boxed{D^{3+\alpha}}$ where

$$\boxed{D = \frac{1}{\gamma\left(1 - \frac{v}{c}\cos\theta\right)}.}$$

- Gamma-ray bursts are the most luminous events known, even accounting for their Doppler beaming, and originate from the formation of black holes, either from merging neutron stars (short GRBs) or supernovae core collapse (long GRBs).

Next time

Neutron stars and pulsars