

Beaming is astrophysically important as it alters required energetics:

- ULXs (ultraluminous X-ray sources) - Bright X-ray sources outside ~~stars~~ galactic nuclei. If they are stellar-mass black holes, their accretion violates (or appears to) the Eddington limit.

**M82**

Several dozen ULXs known in nearby galaxies. Some may be black holes of "intermediate" mass, larger than can be produced by death of single star. Others (probably the majority) may be lower-mass stars that somehow exceed Eddington limit. Easiest way is if their radiation is collimated, or not isotropic. Relativistic beaming would be even more helpful.

- Gamma-ray bursts:

Last from 0.01 to few 1000 seconds,

up to a few can be seen per day.

**GRB animation**

Prompt emission in gamma-rays down to hard X-rays; delayed emission found at lower energies. Total fluence (= flux x duration) for GRBs up to few  $10^{-7} \text{ J m}^{-2}$ .

Initially thought to be Galactic in origin, perhaps from neutron stars (some neutron stars do produce rapid x-ray flaring).

However, GRBs found to be isotropic on sky, ruling out Galactic source. Fast responses enabled identification with distant galaxies, connection to supernovae.

**BATSE GRBs**

**Swift**

**Stanek spectra**

Problem: total emission from GRBs is large

Consider GRB 080319B. (Name gives date; March 19, 2008.)

Host galaxy 7.5 billion light-years away.

Using correct cosmology, that's a luminosity distance of  $6 \text{ Mpc} = 6 \times 10^6 \text{ pc} = 1.8 \times 10^{23} \text{ m}$ . Fluence of  $6 \times 10^{-7} \text{ J m}^{-2}$ .

So total inferred energy release  $E = 4\pi d^2 \times \text{fluence}$

is  $2.6 \times 10^{47} \text{ J}$ , in  $\gamma$ -rays;

this is 10 times the typical energy ( $3 \times 10^{46} \text{ J}$ ) released

in a SN, which is mostly radiated in neutrinos.

The maximum energy available from matter

is  $E = mc^2$ ; for  $1 M_{\odot}$ ,  $E = 2 \times 10^{47} \text{ J}$ , so this would require converting an entire solar mass into radiation at  $\sim 100\%$  efficiency.

Obvious escape route in anisotropy, specifically beaming. Relativistic emitter beams radiation

into  $\Theta_{\text{beam}} \sim \frac{1}{\gamma}$ .

Observer thus sees only small patch  $\Theta \sim \frac{1}{\gamma}$  of (hypothetical) spherical surface of emitter.

As emitter slows while expanding,

Expanding sphere demo

$\gamma$  decreases &  $\Theta$  grows. If emitting material is a beamed jet, then as  $\Theta$  grows it will reach a non-radiating part of the (hypothetical) emitting sphere.

This will cause a change in the rate of decline of the lightcurve, a "break".

Jet breaks

This break, which is a geometric effect, won't depend on frequency — seen in all bands.

Can infer the opening angle from the lightcurve, (with assumptions about external density & energy of jet); typically infer angles  $\sim 6^\circ$ , indicating  $\gamma \sim 10$ .

Since  $\delta \sim \gamma$  (for material beamed directly at us), we can compute true emitted freq., power, etc.

Opening angle is key to understanding power (why?)

For  $Z$  jets, angle covered by jets on sky is  $\frac{\pi \times (\theta_r)^2 \times Z}{4\pi \text{ steradians}} = \frac{\pi (0.1)^2 \times 2}{4\pi} = 0.005$

so required energy is reduced by 0.005 factor.  
Energy release of GRB 080319B drops to  $1.3 \times 10^{45}$  J, about the energy of expanding ejecta in a typical SN.

### Energy of GRBs

Requires  $\sim 200$  times more GRBs in universe than seen. Others would be off-axis to us, observed as peculiar supernovae.

- Blazars are AGN with jets pointed toward us. Spectrum typically flat, no features. Strong  $\gamma$ -ray emission. Interpreted as synchrotron & synchrotron self-Compton peaks, with strong boosting.

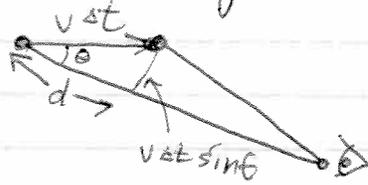
### Blazar SED

Often rapidly variable, but note that timescales are relativistically compressed, so light-travel time arguments can be misleading.

- Microquasars - stellar-mass black holes with jets. Produce "superluminal" motion, knots appearing to move faster than  $c$ .

GRS  
1915+105

Apparent speed caused by relativistic time compression.



We see blob move  
an apparent distance  
 $v(\Delta t) \sin \theta$ , while its  
actual travel is  $v\Delta t$ .

We also see a decreased time to move this distance;  
in reality,  $\Delta t$ , but we see  $\Delta t_A = \Delta t - d/c$ ,

$$\Delta t_A = \Delta t - \frac{v(\Delta t) \cos \theta}{c} = \Delta t(1 - \beta \cos \theta)$$

So we can calculate apparent velocity,  $V_{App} = \frac{v \Delta t \sin \theta}{\Delta t(1 - \beta \cos \theta)}$ ,

$$\text{or } \boxed{V_{App} = \frac{v \sin \theta}{1 - \beta \cos \theta}} \quad \beta_{app} = \frac{\beta \sin \theta}{1 - \beta \cos \theta}$$

For  $\theta = 0$ ,  $\beta_{app} = 0$  (no motion), if  $\theta = \pi/2$ , then  $\beta_{app} = \beta$  (~~we're~~  
(we're staying in observer frame always).

But for  $\beta = 0.99$ ,  $\theta = 8.1^\circ$  gives  $\beta_{app} = 7.0$ .

Note that if jets are produced in  $Z$  directions, one  
tilting towards us, only one will show superluminal  
motion & intensity boosting, other will be de-boosted  
& appear slower. Often only one jet is seen in  
jet systems.

## Acceleration of particles to high energies

Origin of relativistic particles is not fully understood,  
Some acceleration provided by pulsar B fields.

Can this reach observed  $\gamma$ ?  
Use Crab's observed  $\gamma$  properties,