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PHY418 PARTICLE ASTROPHYSICS

Sources

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Sources of high-energy particles

- We now have clear observational diagnostics for particle acceleration
 - synchrotron radiation (radio, sometimes X-ray)
 - inverse Compton scattering (X-ray, γ -ray)
 - π^0 decay (γ -ray, neutrinos)
- We have acceleration mechanisms
 - Fermi 2nd order, DSA, SDA, relativistic shocks, magnetic reconnection
- How do these come together in astrophysical environments?

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SOURCES

The solar system

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notes section 4.2

Shocks in the solar system

- Various different types of collisionless shocks are seen in the solar system
 - they do accelerate particles (to fairly modest energies)
 - they have the advantage that we can study them directly with spacecraft

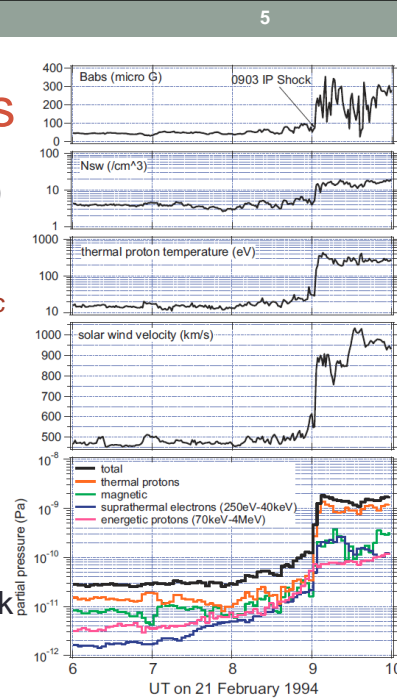
a: CME shocks
 b: Van Allen belts
 c: heliospheric shocks
 d: Earth's bow shock
 e: Earth's magnetotail
 f: Earth's foreshock

Hillas relation seems to be a good guide to maximum energies (except for CME shocks)

| Point | $E_{max,Hillas}$ (eV) | $E_{max,obs}$ (eV) |
|-------|-----------------------|--------------------|
| f | 10^5 | 10^5 |
| e | 10^6 | 10^6 |
| d | 10^7 | 10^7 |
| c | 10^8 | 10^8 |
| b | 10^9 | 10^9 |
| a | 10^{11} | 10^{11} |

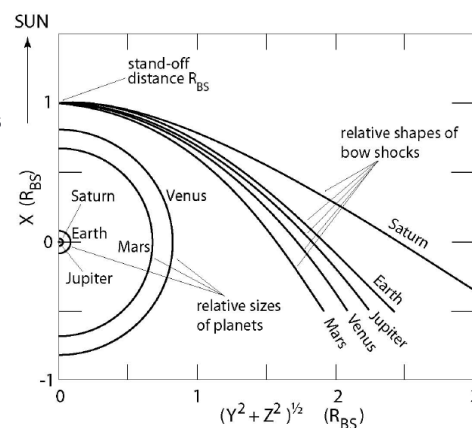
Solar flares and CMEs

- “Solar energetic particles” (SEPs) are associated with solar flares
 - not emitted by Sun itself but accelerated by magnetohydrodynamic shocks accompanying flare event
- At least two acceleration mechanisms believed to operate
 - DSA in CME-driven interplanetary shocks (“gradual” SEP events)
 - magnetic reconnection in flare itself (“impulsive” events)
- Evidence for modification of shock front by accelerated particles



Planetary bow shocks

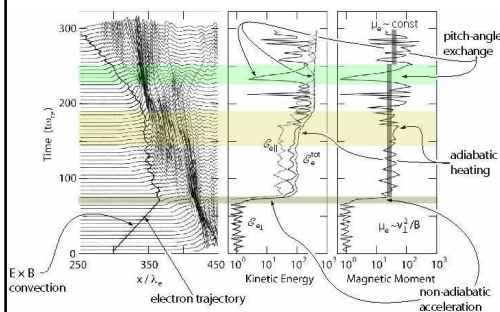
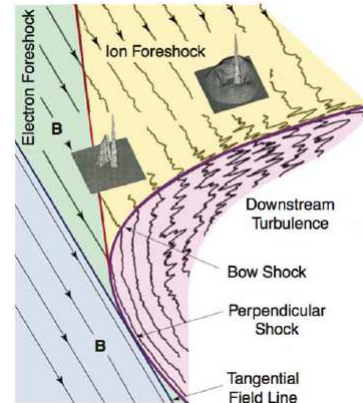
- Occur when the supersonic solar wind encounters an obstacle
 - this needs to be something conductive
 - the magnetosphere for planets with magnetic fields (Mercury, Earth, the giants)
 - ionosphere for non-magnetic planets with atmospheres (Venus, Mars, also comets)
 - rocky bodies without atmosphere have no bow shock (Moon, asteroids)



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Planetary bow shocks

- Bow shock geometry varies across shock
 - expect DSA to operate in quasi-parallel geometry region, SDA in quasi-perp.
 - observe *field-aligned beams* of ions probably originating from SDA

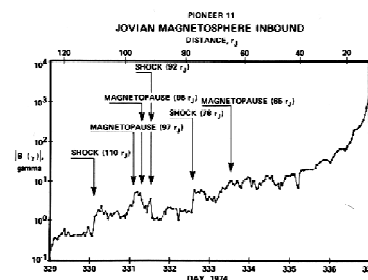
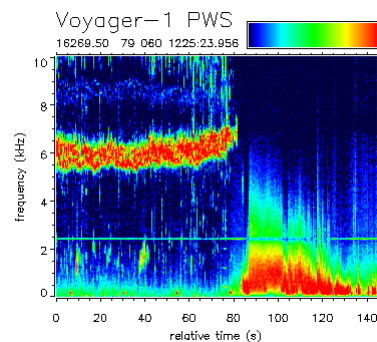


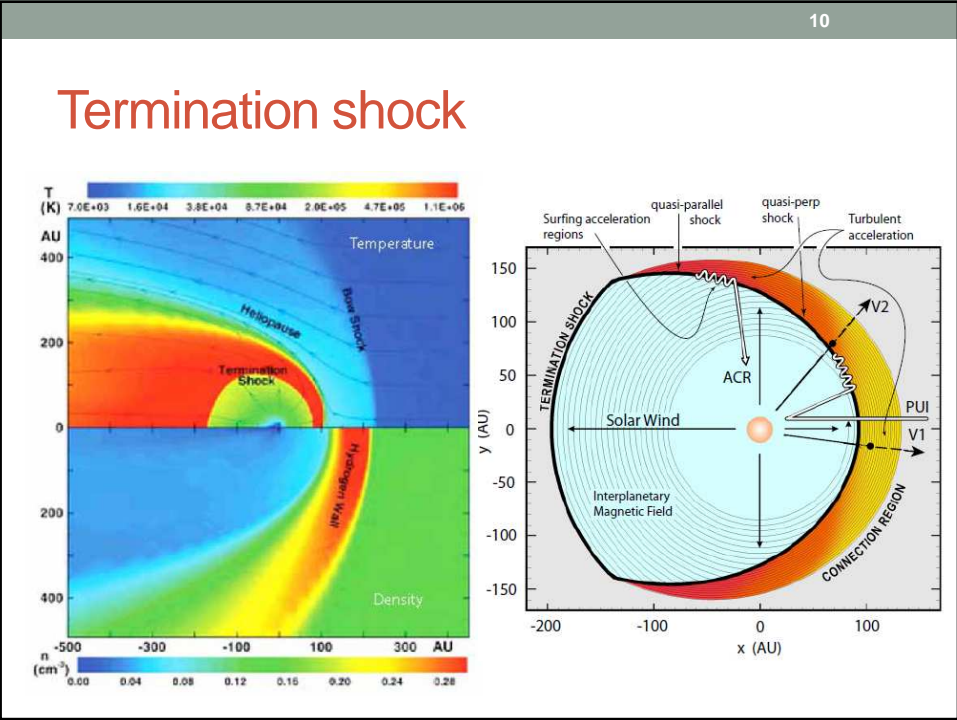
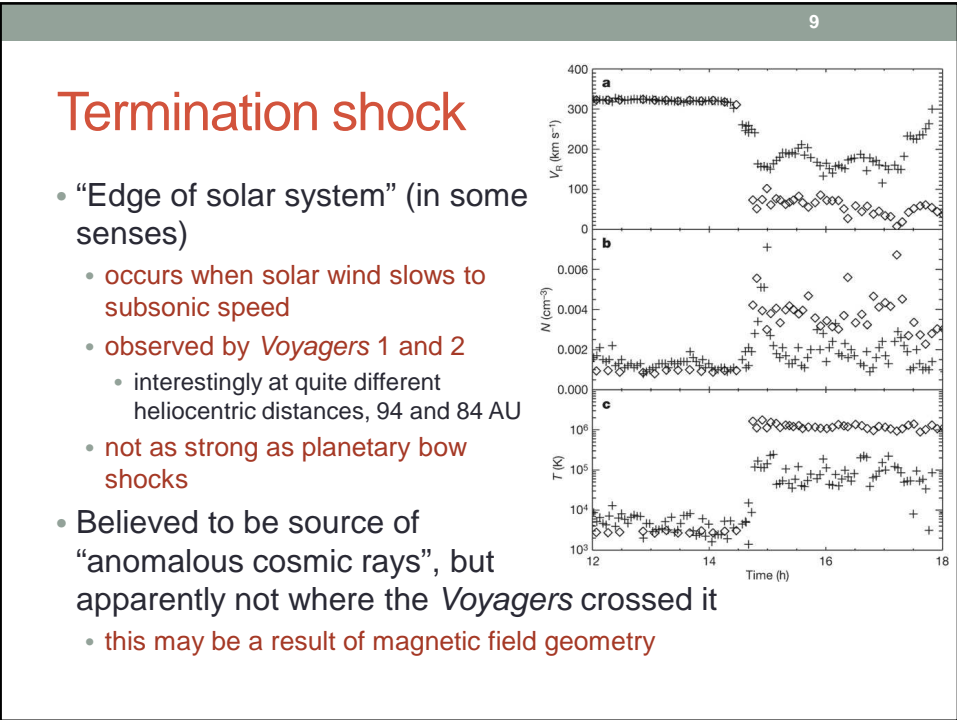
Simulation of electron acceleration by “shock surfing” in quasi-perpendicular shock

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Planetary bow shocks

- Jupiter and Saturn have extensive magnetospheres strongly influenced by fast rotation (~10 hr)
 - studied originally by Pioneer 10/11 and Voyager 1/2 flybys, then by Galileo and Cassini probes
- Small (ionosphere-generated) bow shocks of Mars and Venus also studied
 - interaction of solar wind with Martian atmosphere may contribute to early loss of atmosphere—though clearly this did not happen to Venus!



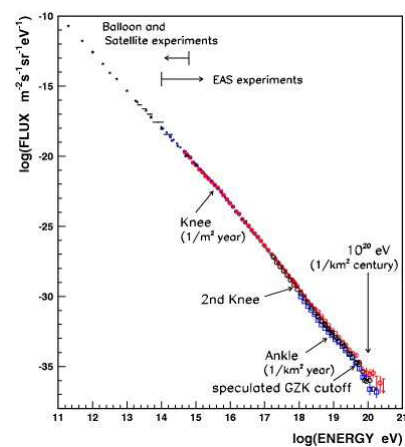


GALACTIC SOURCES

Supernova remnants

Supernovae and supernova remnants

- Galactic SNRs are believed to be the source of cosmic rays up to the “knee” at $\sim 10^{16}$ eV
- Rate of supernovae in Galaxy adequate to supply required energy if they are $\sim 10\%$ efficient in converting explosion energy to CRs
 - this is quite high but consistent with simulations of diffusive shock acceleration



Classification of supernovae

| No hydrogen | | Early hydrogen | Hydrogen always present | | | |
|-------------|-----------|----------------|-------------------------|-------------|-------------|--------------|
| Si II | No Si II | | | Light curve | | Narrow lines |
| | He | No He | | Plateau | Linear | |
| Ia | Ib | Ic | IIb | II-P | II-L | IIIn |

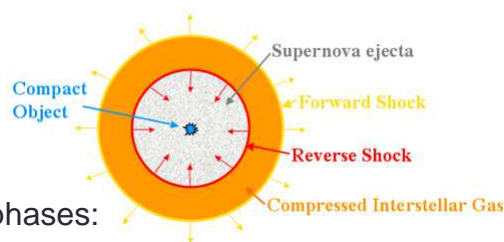
thermo-nuclear

massive star core collapse

All types of supernovae form supernova remnants (expanding shells of gas), but only CCSNe form compact objects (neutron stars/black holes)

Evolution of supernova remnants

- Supernova blast wave is highly supersonic
 - forward shock develops at its leading edge
- Three main evolutionary phases:
 - **free expansion (ejecta-dominated)**
 - forward shock has swept up relatively little ambient gas, expansion velocity nearly constant (does decelerate slightly)
 - **Sedov or Sedov-Taylor phase**
 - mass of swept-up material becomes comparable to ejecta mass
 - forward shock decelerates, reverse shock generated
 - **radiative phase**
 - shock slows to ~200 km/s, significant energy loss through emission lines
- Particle acceleration probably only in first two phases



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Evolution of supernova remnants

- Numbers:

- Initial speed of blast wave

$$V_0 = \sqrt{\frac{2E_{SN}}{M_{ej}}} = 10^4 \left(\frac{E_{SN}}{10^{44} \text{ J}} \right)^{1/2} \left(\frac{M_{ej}}{1M_{\odot}} \right)^{-1/2} \text{ km/s}$$

- Sound speed

$$c_s = \sqrt{dP/d\rho} = 10\sqrt{T/1 \text{ eV}} \text{ km/s}$$

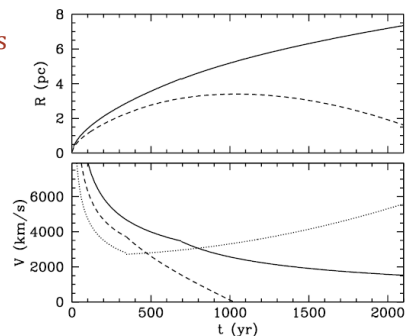
- shock has Mach number ~ 1000

- Sedov phase starts when swept-up ISM comparable to ejecta, i.e.

$$\frac{4}{3}\pi\rho_{ISM}R^3 = M_{ej}$$

- this gives $R \sim 2 \text{ pc}$, $t \sim 200 \text{ yr}$
(for $M_{ej} = 1 M_{\odot}$ and $n = 1 \text{ cm}^{-3}$)

- ends $\sim 28000 \text{ yr}$ when radiative cooling time \sim SNR age



notes section 4.3.3

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Observational evidence

- Historical supernovae

- naked-eye observations for SNe 1604 (Kepler's), 1572 (Tycho's), 1181, 1054, 1006 (also 393, 386, 185?)

- two young remnants not seen as SNe (Cas A, ~ 1680 , G1.9+0.3, ~ 1870)

- Radio

- most SNRs are observed at radio wavelengths

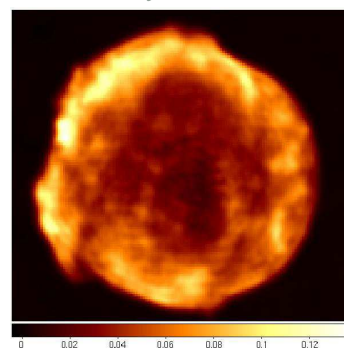
- 294 in standard catalogue (Green), only 20 have insufficient data for radio flux

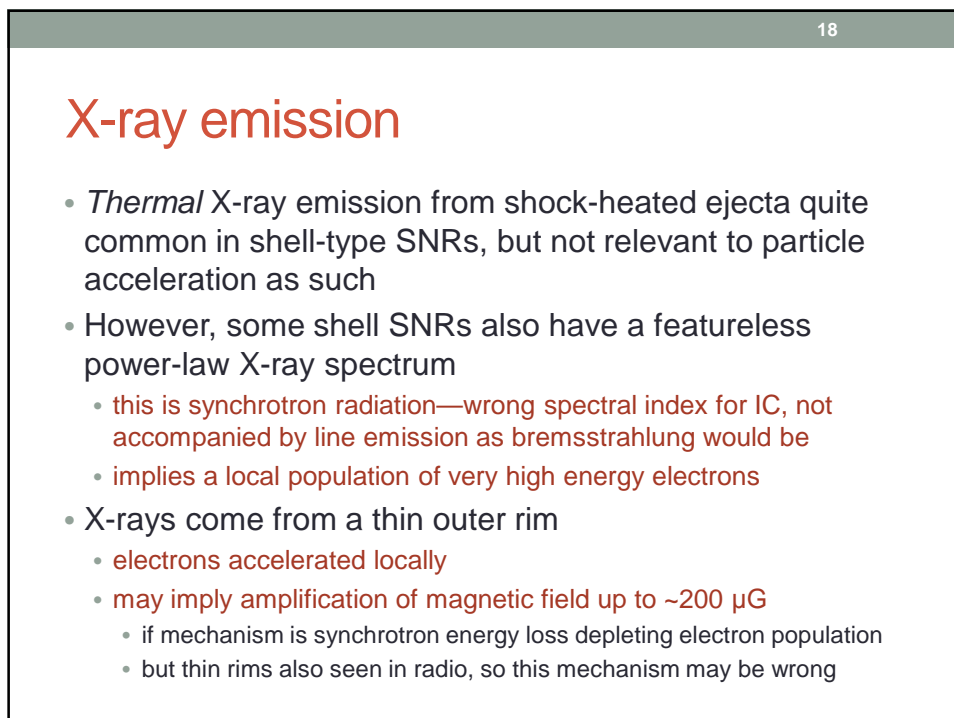
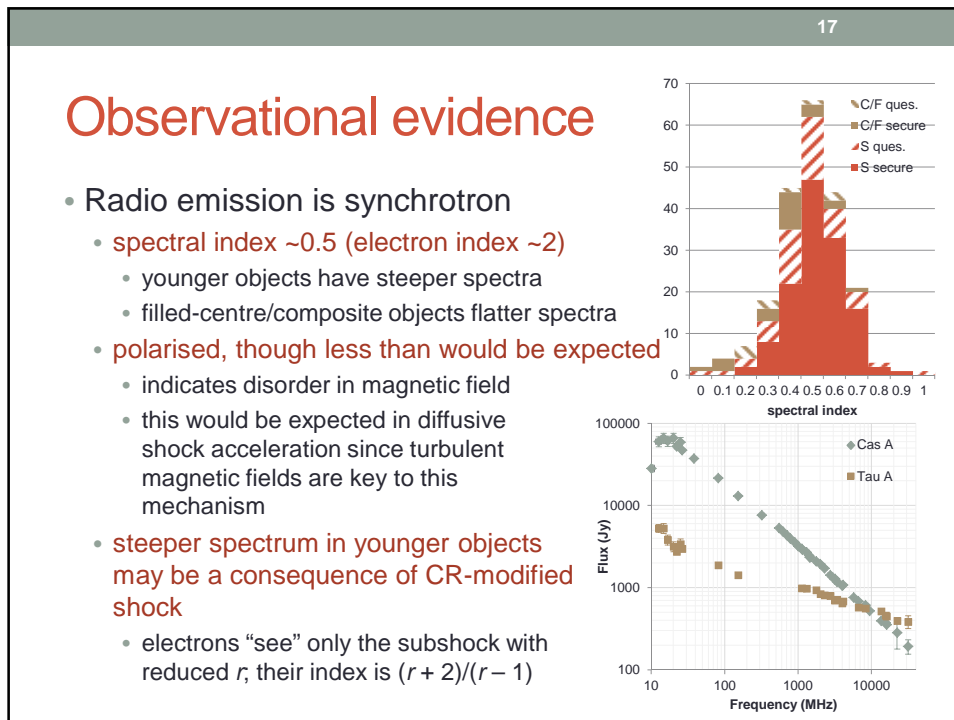
- 80% shell-type, 12% composite, 3% filled-centre (remainder unclassified)

- $\sim 40\%$ also observed in X-rays, $\sim 30\%$ in optical

- lack of detectable optical emission is partly due to location of massive stars close to Galactic plane, where there is a lot of dust absorption

Tycho at 1.5 GHz

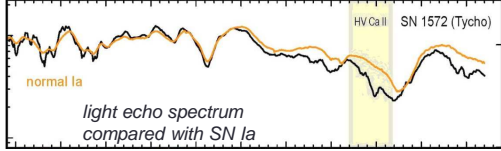


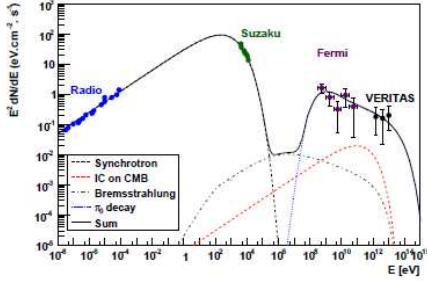


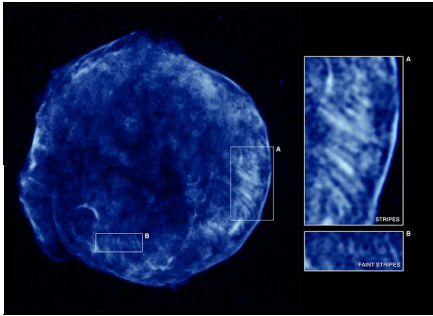
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X-ray emission

- Tycho's SNR (1572)
 - SN Ia (spectrum observed as "light echo")
 - γ -ray emission suggests π^0 decay
 - "stripes" in X-ray image spaced by $\sim 8''$
 - if these features are caused by proton gyroradius, then for B-field of $30 \mu\text{G}$ $E_p = 2 \times 10^{15}$ eV (knee)
 - some fits to radio/X-ray spectrum suggest $B \sim 300 \mu\text{G}$



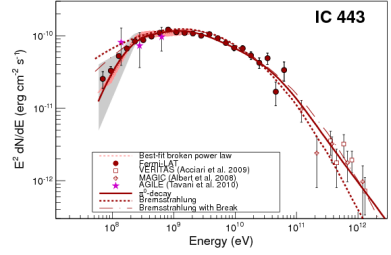


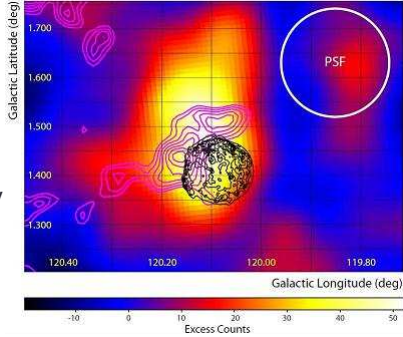


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GeV and TeV emission

- Most shell SNRs do not emit high-energy photons
- Exceptions:
 - young objects such as Tycho
 - hard spectra, bright in TeV range
 - SNRs interacting with molecular clouds
 - softer spectra, more luminous in GeV





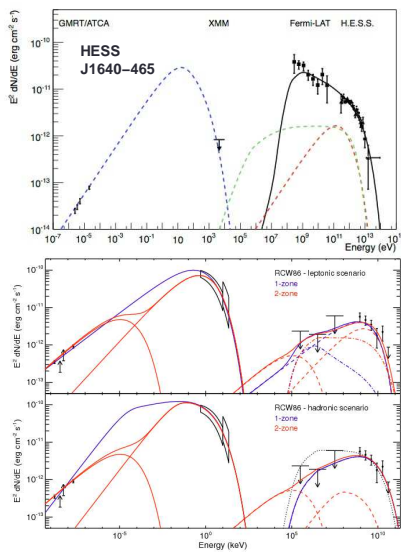
Both Tycho and IC 443 have high-energy spectra best fitted by π^0 decay. However, other young SNRs such as RXJ1713-3946 have IC spectra

IC443

Bob Franke, <http://bf-astro.com/ic443sho.htm>

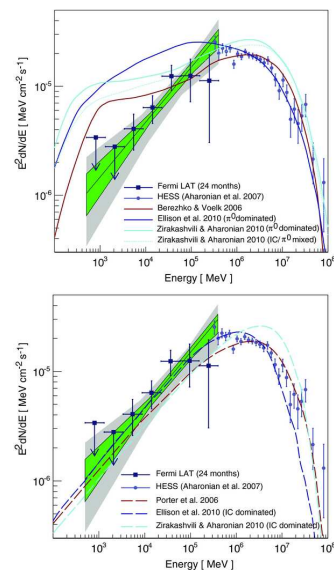


GeV and TeV emission



Observations at GeV energies are essential to distinguish IC and π^0 hypotheses.

Note that IC-dominated spectra don't necessarily mean that remnants do not accelerate cosmic rays!



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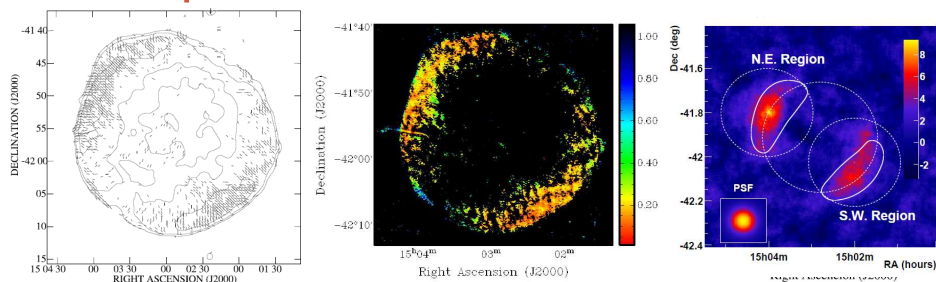
Conclusion: SNRs

- Supernovae occur about once every 40 years on average ($\pm 50\%$) and release about 10^{44} J of energy each
 - this is sufficient to account for cosmic rays up to the knee if SNRs are about 10% efficient in converting this energy into cosmic rays
- The supernova blast wave is highly supersonic and will produce a forward shock
 - subsequently also a reverse shock as the forward shock is decelerated by the ambient interstellar medium
 - the shock is seen in young SNRs as a sharp edge in synchrotron emission
- SNRs do accelerate particles
 - synchrotron emission seen in radio, and in young SNRs also in X-rays
 - GeV and TeV γ -rays emitted by young and interacting SNRs
- Properties are broadly consistent with diffusive shock acceleration
 - right synchrotron spectral index and combination of shock and B-field

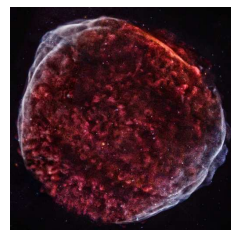
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Example: SN 1006

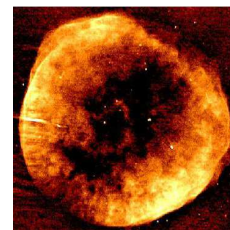
Also seen in TeV γ -rays by HESS



- Remnant of the brightest supernova ever observed
- Polarisation lower in regions where particles are being accelerated
- These appear to be regions of quasi-parallel geometry
- Note “thin rim” in both X-ray and radio



Chandra, X-ray



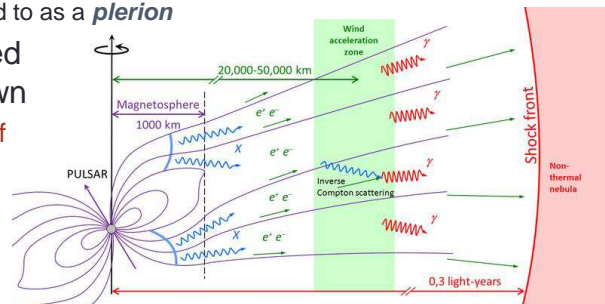
VLA+ATCA, radio

GALACTIC SOURCES

Pulsar wind nebulae

Pulsar wind nebulae

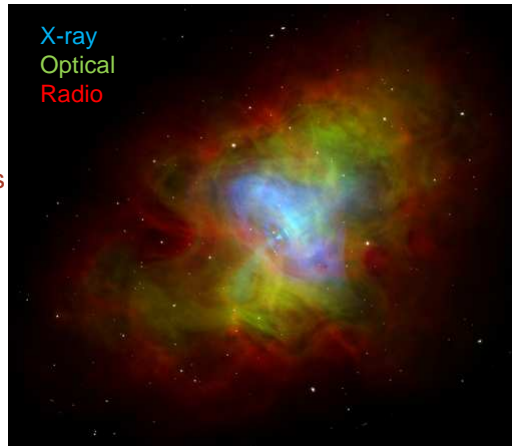
- Pulsars are rapidly spinning neutron stars with strong magnetic fields
 - they have enough energy to produce an e^+e^- “pair plasma” and a relativistic wind, which generates a shock when it hits either supernova ejecta or ambient interstellar medium
 - this produces a **pulsar wind nebula (PWN)**
 - sometimes referred to as a **plerion**
- PWNe are powered by pulsar spin-down
 - not by the energy of the original SN as in shell-type SNRs



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Pulsar wind nebulae

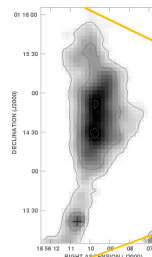
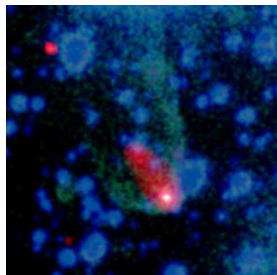
- The classic PWN is the Crab Nebula (SN 1054)
 - The Crab is seen at all wavelengths from TeV to radio—it was one of the first radio sources identified with a known object
 - It is powered by a pulsar with 33 ms period
 - Despite extensive searches no shell SNR is found
 - extremely unexpected, as would expect a young SN II remnant to have a shell
 - maybe this was an atypical SN II



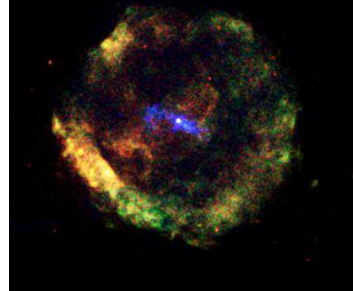
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Pulsar wind nebulae

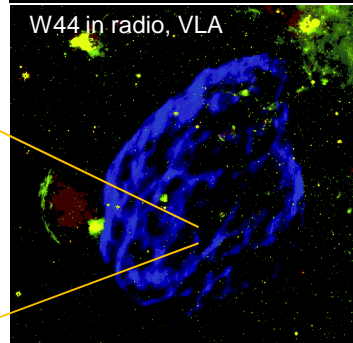
- “Composite” SNRs contain a PWN surrounded by a shell SNR
 - PWN will be central in young SNRs, but not in older examples because asymmetric SNR explosion imparts a “kick” to the pulsar
 - older pulsars may have a “bow shock” PWN with no SNR



G11.2-0.3 by Chandra



W44 in radio, VLA

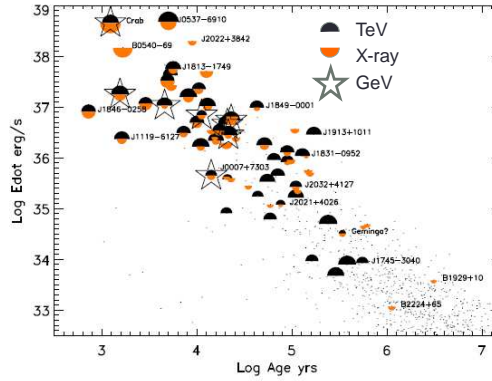


High energy photon emission

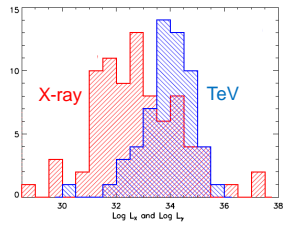
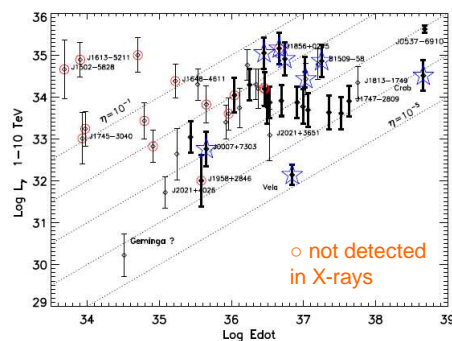
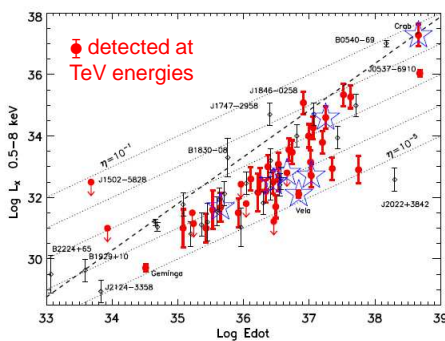
- Energy source is pulsar spin-down

$$\frac{dE}{dt} = 4\pi^2 I \frac{dP/dt}{P^3}$$

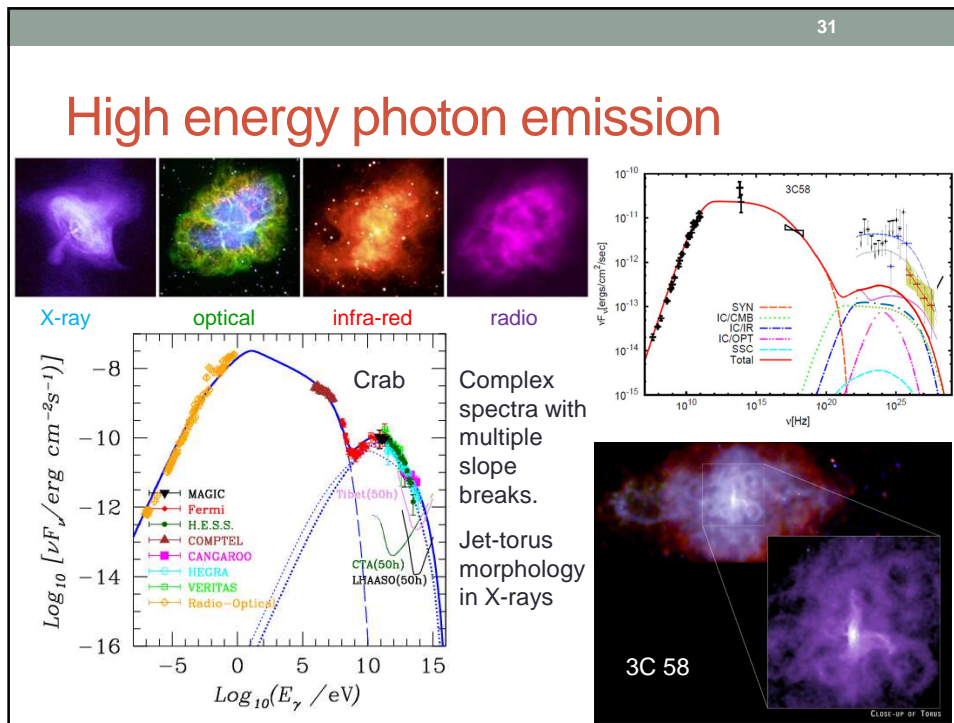
- I is pulsar moment of inertia (10^{38} kg m² for mass $1.4M_{\odot}$ and radius 10 km)
- typically only pulsars with fairly high dE/dt generate obvious PWNe
- Surprisingly little correlation between L_X and L_{TeV}
 - L_X shows some correlation with dE/dt , L_{TeV} really doesn't



High energy photon emission



- Luminosity at TeV energies is on average somewhat higher than in X-rays
- Both TeV and X-ray emission are basically power laws, with photon index ($dN_{\gamma}/dE \propto E^{-\Gamma}$) typically 2-2.7 for TeV, 1-2 for X-rays



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Particle acceleration in pulsar wind nebulae

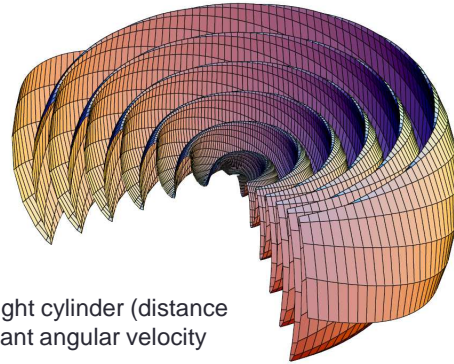
- Basic principles:
 - pulsars have a very large magnetic field and rotate extremely rapidly
 - this induces an extremely large electric field which rips particles off the surface of the pulsar and accelerates them to high energies
 - in the high-density pulsar wind these accelerated primary particles induce an electromagnetic shower, producing a "pair plasma" dominated by e^+ and e^- (rather than p and e^- as in a normal plasma)
 - plasma escapes along open field lines, producing a relativistic pulsar wind

The diagram illustrates the structure of a pulsar. A central yellow sphere represents the Neutron star. A vertical blue arrow indicates the Rotation axis. A horizontal cylinder represents the Light cylinder, with a radius of approximately 130 stellar radii. Magnetic field lines are shown as curved lines originating from the poles of the neutron star. The regions between the poles are labeled as the Polar cap region, Outer gap region, and Slot gap region. The field lines are divided into Closed field lines and Open field lines. The magnetic field is shown as a vector field.

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Particle acceleration in pulsar wind nebulae

- Pulsars are oblique rotators—magnetic and rotation axes not parallel
 - this produces a time-varying electromagnetic field which propagates outward as an EM wave with wavelength $\leq 2\pi r_L$
 - $r_L = cP/(2\pi)$ is the radius of the light cylinder (distance from rotation axis at which constant angular velocity would require $v = c$)
 - net result of this is a **striped wind** consisting of two spirals of opposite magnetic polarity
 - this propagates outward to a *termination shock* where it hits either supernova ejecta or ISM:



$$r_{TS} = \dot{E} / (4\pi\eta cp)$$

η = fraction of solid angle covered by wind
 p = pressure outside shock

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Particle acceleration in pulsar wind nebulae

- PWNe unquestionably accelerate particles
 - radio and X-ray synchrotron emission, TeV photons
- But it's quite hard to work out how they do it
 - magnetic geometry at the termination shock must be quasi-perpendicular, which disfavours diffusive shock acceleration
 - but maybe enough small-scale turbulence is generated at the shock
 - the expected electron power law of $E^{-2.2}$ is right for the Crab's X-ray spectral index (though not for its much flatter radio index)
 - opposed magnetic fields in the striped wind suggest reconnection
 - acceleration by magnetic reconnection in relativistic plasma is not yet well understood—not clear if it can generate required spectrum
 - **resonant cyclotron absorption**
 - ion-dominated “cold” (i.e. very ordered) winds produce cyclotron waves that are resonantly absorbed by e^+e^- (doesn't accelerate ions)
 - hard to justify required injection rate of ions

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Conclusion: PWNe

- Pulsar wind nebulae are important sources of high energy photon emission in the Galaxy
 - this emission is powered by the pulsar spin-down
- They can be associated with SNRs, but some are isolated pulsars with “bow shocks”
 - there are various ways in which a pulsar can be “kicked” out of its SNR (asymmetric explosion, asymmetric reverse shock)
 - also, the most famous PWN of all—the Crab—has no associated shell SNR despite not having moved much from observed SN
- The exact acceleration mechanism is disputed
 - hence it is not obvious if PWNe accelerate ions, or just e^+e^-
- Note that e^+ escaping from PWNe might account for the “positron excess” in cosmic rays

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EXTRAGALACTIC SOURCES

Gamma ray bursts

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Gamma-ray bursts

Bursts are very variable in duration and shape

- Discovered in 1973 following several years of observations by *Vela* defence satellites
 - these were designed to look for γ rays from clandestine nuclear tests
 - relative timing of detections from different satellites made it clear that source was extra-terrestrial
- Diagnostic feature: burst of soft (MeV) γ -rays

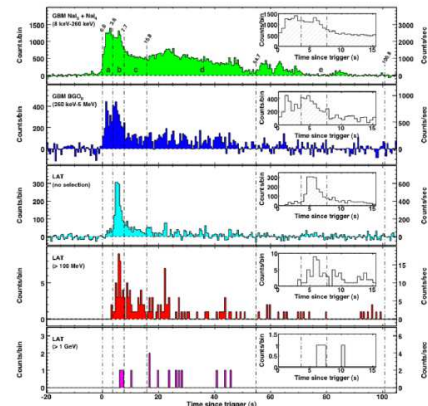
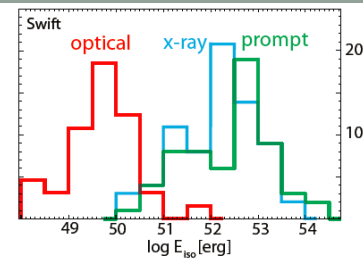
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Distribution

- BATSE instrument on CGRO (1991-2000) catalogued over 2700 GRBs
 - isotropic in space
 - either very local or extragalactic
 - bimodal time distribution
 - “short” bursts, 90% of the energy within < 2 s; “long” bursts, > 2 s
- BeppoSAX (1996-2003) detected X-ray afterglows with higher positional accuracy
 - identified sources; confirmed GRBs are extragalactic

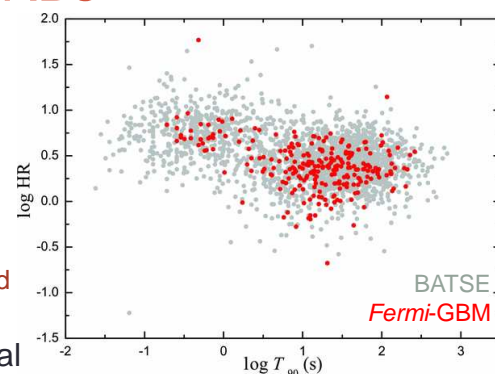
Gamma-ray emission

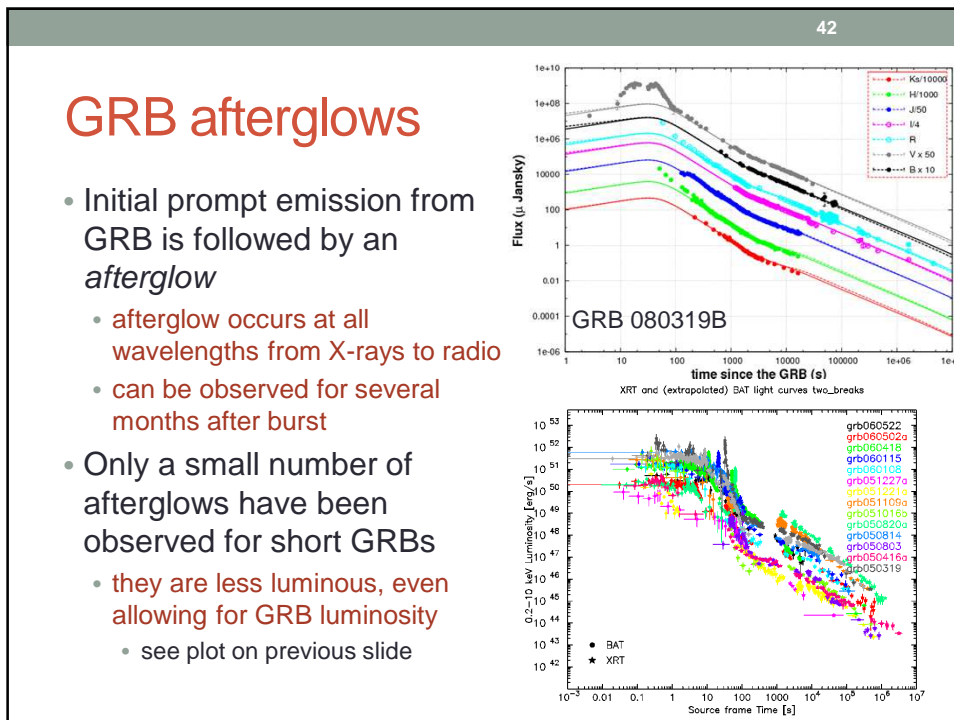
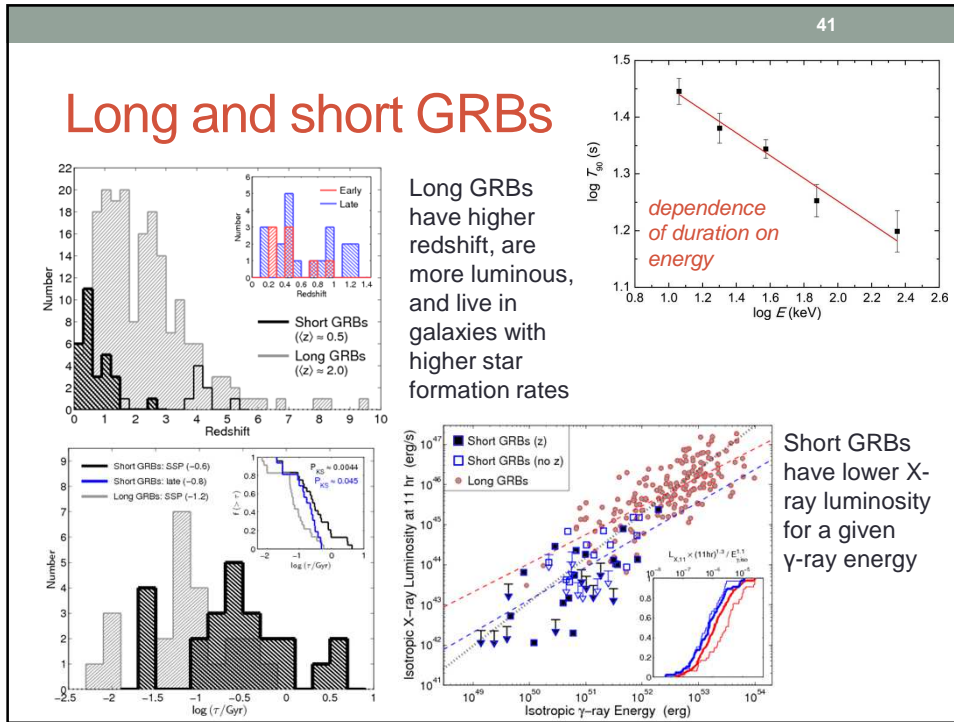
- The GRB proper is in *soft* γ -rays (0.1–10 MeV)
 - the spectrum peaks at ~ 1 MeV
 - a minority of bursts also emit GeV γ -rays, but these are later than the main burst
 - no GRBs have been seen to emit TeV photons
 - this is not a very stringent limit:
 - high redshift GRBs lie beyond the range limit for VHE photons
 - only a fraction of bursts can be observed owing to low duty cycle of air Cherenkov telescopes



Long and short GRBs

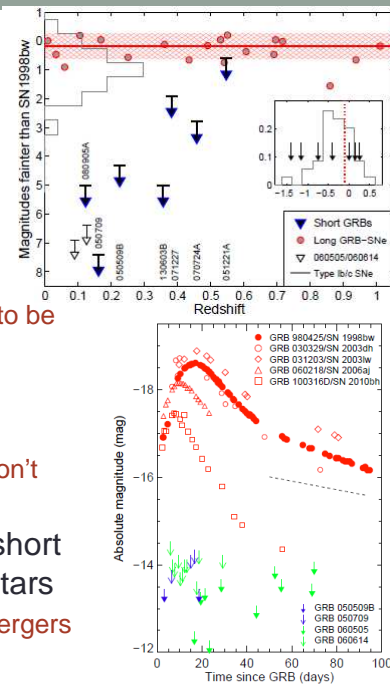
- The 2 s boundary is a bit artificial
 - it is different in different energy ranges
 - high z GRBs are affected by time dilation and may move from “long” as observed to “short” in their rest frames
- But the two classes are real
 - “short” GRBs have harder spectra and differ in many other respects (distance, luminosity, host galaxy properties) from “long” GRBs
- Evidence indicates different progenitors for the two classes





GRB progenitors

- A number of long GRBs have been clearly associated with supernovae
 - light curves and spectra of SNe show them to be Type Ibc, but they appear to be brighter than typical SNe Ibc
- Short GRBs are definitely *not* associated with SNe
 - and there are a few long GRBs that don't seem to have associated SNe either
- Diversity of host galaxies shows short GRBs are not linked to massive stars
 - currently favoured model is NS-NS mergers



GRB models

- GRB emission **must** be beamed
 - rapid variability implies small source size (< 300 km)
 - photon energies extend beyond $2m_e c^2$ (~ 1 MeV) with no cut-off
 - this means that pair conversion is possible
 - with photon density as implied by luminosity, photons above 1 MeV or so should be heavily depleted by $\gamma\gamma \rightarrow e^+e^-$
 - this clearly is not happening
 - conclusion: source region must be expanding relativistically
 - for Lorentz factor Γ , this increases size scale by Γ^2 , decreases opacity by Γ^4 , and increases pair production threshold by Γ
 - estimated value of Γ is $10^2 - 10^3$
 - a forward shock will certainly occur when this relativistic outflow hits the surrounding medium, and there may be multiple shocks
 - multiple peaks in some GRB light curves suggest this

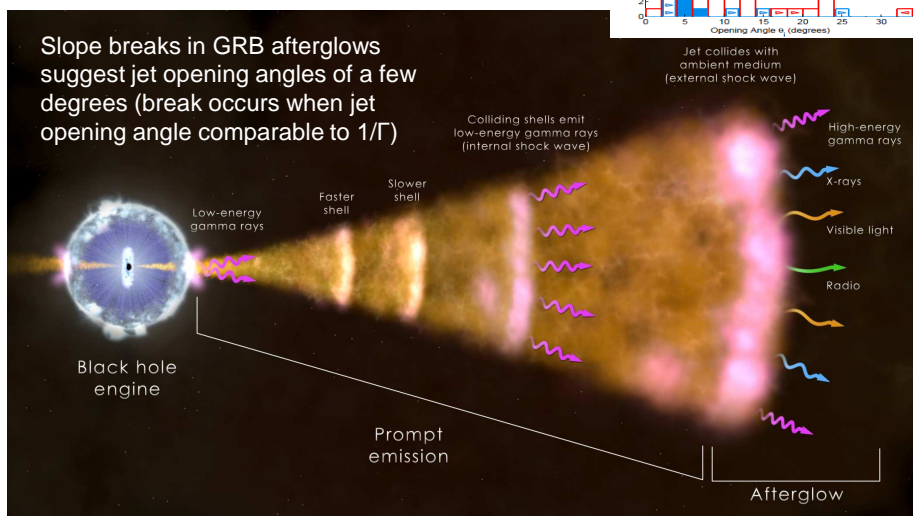
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Particle acceleration in GRBs

- The central engines of long and short GRBs are similar (formation of a black hole)
 - the different properties are probably caused by the difference in environment, plus perhaps difference in mass of BH
- The emission is probably all synchrotron
 - not sure about the GeV range—might be inverse Compton
- A beamed relativistic outflow seems essential to explain the observations
 - relativistic shocks generate turbulence through plasma instabilities
 - this provides a suitable environment for particle acceleration
 - acceleration at relativistic shocks can be very fast, because of $\sim\Gamma^2$ gain at first return crossing
 - prompt γ -ray emission may be generated at internal shock, afterglow at external shock

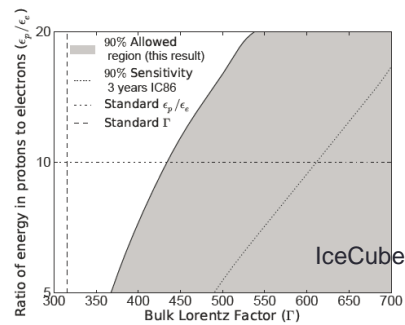
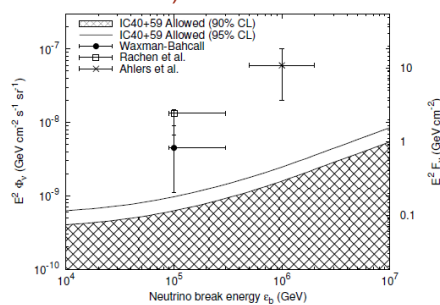
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GRB models



Hadron acceleration in GRBs?

- Synchrotron (+SSC?) spectrum requires only electrons
 - no π^0 decay signature
- IceCube sees no neutrinos associated with GRBs
 - the constraints are starting to be interesting, though other authors argue their predicted neutrino fluxes are too high (and hence limit too low)



Conclusions: GRBs

- GRBs are among the most extreme phenomena in the universe
 - they appear to be generated when the formation of a BH by massive star core collapse or NS-NS merger produces an ultrarelativistic shock
 - conditions for this to happen are not fully understood: statistics show that only a minority of SNe Ibc produce long GRBs (and a minority of long GRBs are not associated with supernovae)
- Particle acceleration is probably associated with relativistic shocks
 - EM spectrum either synchrotron or synchrotron+SSC
 - no evidence for hadron acceleration (but not much against)
 - neutrino limits from IceCube are beginning to look interesting
 - GRBs could be source of UHE CRs, but starting to look less likely

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EXTRAGALACTIC SOURCES

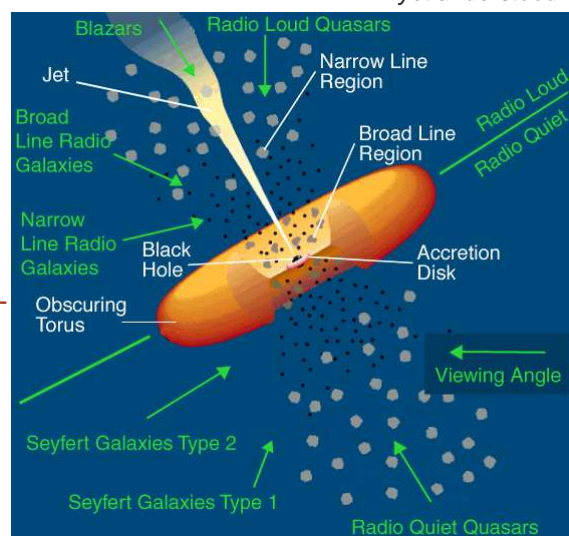
Active galactic nuclei

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Active galactic nuclei

Only a minority of AGN are radio loud, for reasons not yet understood

- Active galaxies are those whose luminosities are not dominated by starlight
 - The power source is believed to be accretion on to a super-massive black hole
- Different types of active galaxy correspond to different orientations

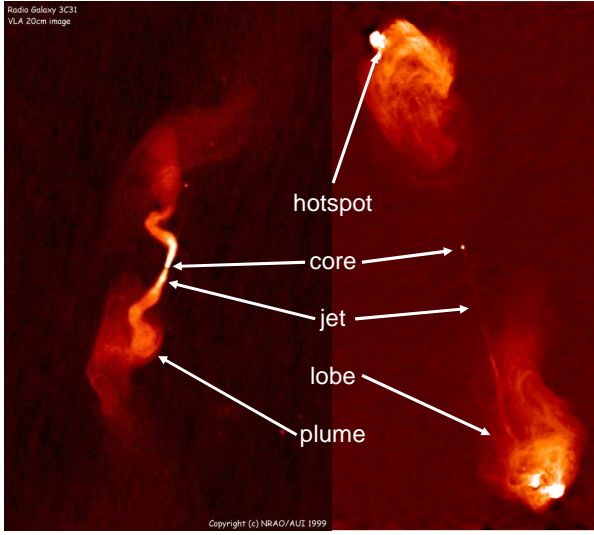


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Radio-loud AGN

FR I
FR II

- Radio galaxies are divided into FR I and FR II
- FR I: low radio luminosity, edge-darkened, bright jets
- FR II: high radio luminosity, edge-brightened, faint or invisible jets with bright hotspots
- some galaxies have >1 jet system (episodic)
- Blazars and FSRQs are similar objects, but viewed down the jet
- in FSRQs see emission lines as well

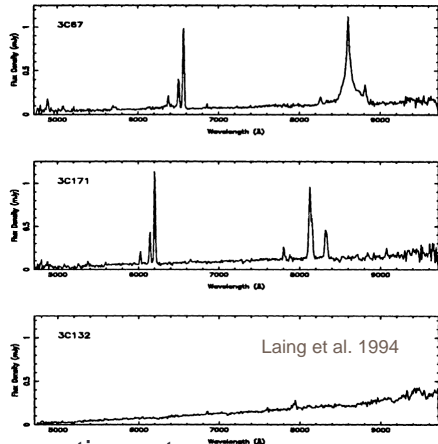


Radio Galaxy 3C31 VLA 20cm image
Copyright (c) NRAO/AUI 1999

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High and low excitation radio AGN

- Most radio quiet and some radio loud AGN have strong emission lines from ionised atoms
 - “high excitation radio galaxies”
 - mostly (but not all) FR II
- Most radio loud AGN do not have these emission lines
 - “low excitation radio galaxies”
 - mostly (but not all) FR I
- This appears to be related to accretion rate
 - HERGs are accreting at a high rate from an accretion disc
 - LERGs are accreting at a low rate from optically thin hot gas

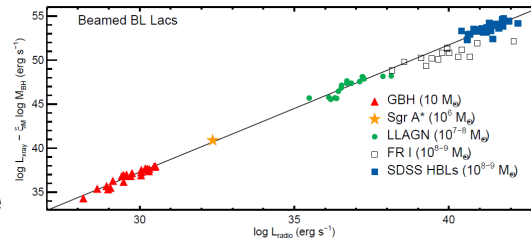


Laing et al. 1994

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Radio and X-ray emission

- Radio emission is synchrotron
 - diagnostic of lepton acceleration
- X-ray emission is more complicated
 - there is a power law (synchrotron? inverse Compton?) but also thermal contributions, e.g. iron K α emission
 - X-ray and radio emission closely related
 - “fundamental plane” relating radio luminosity, X-ray luminosity and black hole mass
 - this holds (with different coefficients) whether X-ray emission is synchrotron emission from the jet or inverse Compton from the corona surrounding the black hole

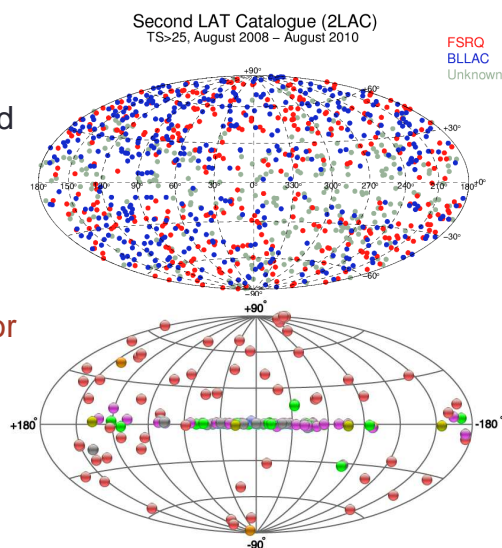


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High energy photon emission

Extragalactic sources reported by *Fermi*-LAT and IACTs are almost all blazars or flat spectrum radio quasars

Radio quiet AGN are not seen; more surprisingly, nor are higher-luminosity FR II radio galaxies



Relativistic bulk motion

- Many AGN jets display apparent superluminal motion

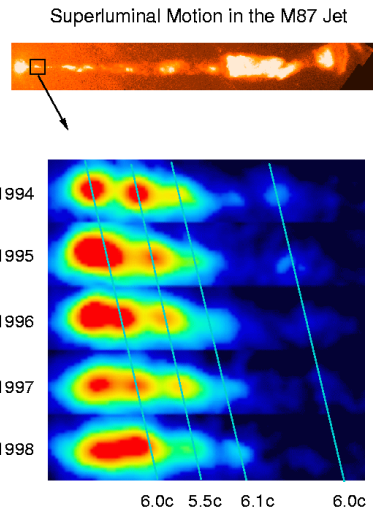
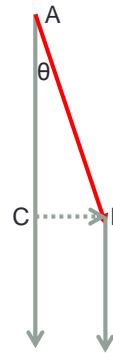
- this is an optical illusion
- if speed of jet is βc , then if hotspot travels distance AB in time Δt , observed time interval between A and B is

$$\Delta t(1 - \beta \cos \theta)$$

- so observed speed is $\frac{\beta c \sin \theta}{1 - \beta \cos \theta}$

- for $\gamma \gg 1$ this comes out to $2\gamma/3$

- Jets aren't superluminal, but they are relativistic



Shocks

- FR II radio galaxies clearly have a **jet termination shock** at the outer hotspots

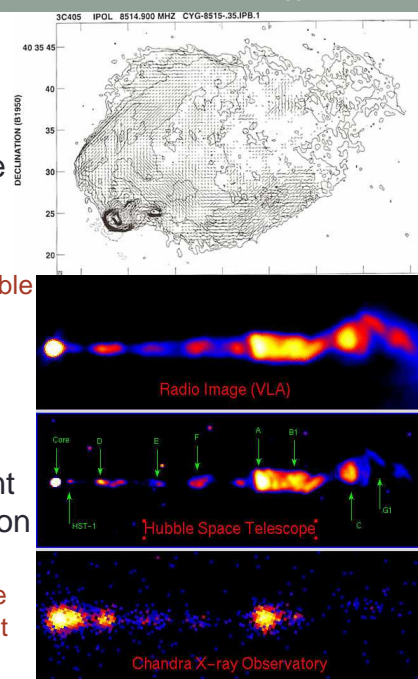
- “Knotty” jets like M87 suggest possible internal shocks too

- These would be relativistic with bulk Lorentz factors ~ 10

- not as relativistic as GRBs

- Presence of shocks is consistent with relativistic shock acceleration

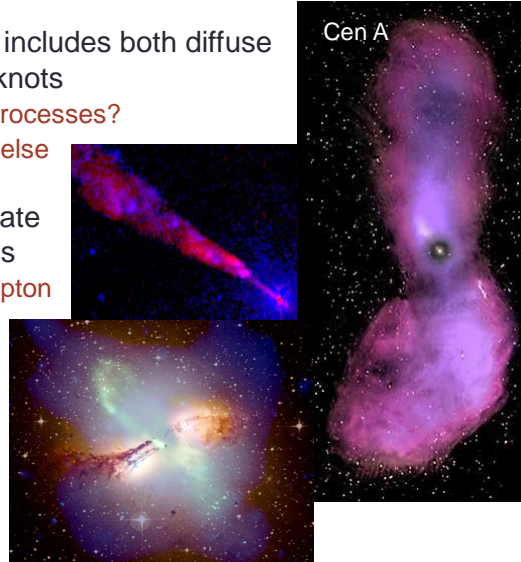
- but X-ray synchrotron emission, especially in FR I galaxies, is diffuse and distributed—not concentrated at shocks



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Particle acceleration in FR I jets

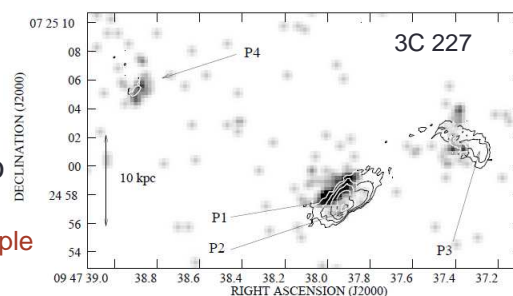
- X-ray emission in FR I jets includes both diffuse emission and small bright knots
 - two different acceleration processes?
 - DSA at shocks, something else for diffuse emission?
- FR I jets appear to decelerate as they propagate outwards
 - model: initially very light (lepton dominated) jet entrains material from hot IGM
- Distributed acceleration may be Fermi 2nd order in turbulent fields
 - magnetic reconnection also possible



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Particle acceleration in FR II jets

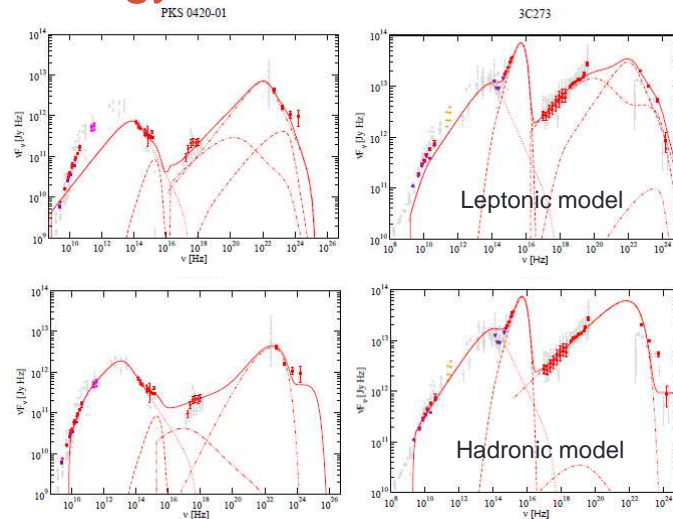
- FR II galaxies have a well-defined termination shock
 - though it is not obvious that it has favourable magnetic geometry
- The “hotspot” behind the shock is bright at radio and X-ray wavelengths
 - X-ray emission is usually synchrotron-self-Compton
 - sometimes also a synchrotron component (needs higher energy e^\pm)
 - this is consistent with acceleration at or near the TS
- Sometimes X-rays are not coincident with radio
 - this may indicate a more complex process than simple shock acceleration



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Spectral energy distributions

- Blazars and FSRQs are very variable
- Fits to leptonic (IC) and hadronic (π^0) models sometimes favour one over the other
 - either way round!
 - usually, both work




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Conclusions: AGN

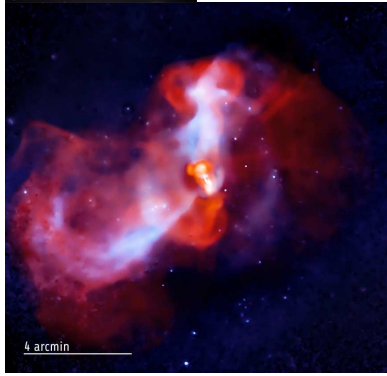
- Radio-loud AGN definitely accelerate particles
 - they produce radio and sometimes X-ray synchrotron emission, and blazars are the dominant source of high-energy γ -ray emission
- AGN jets show evidence of bulk relativistic motion
 - with termination shock in FR II
 - with deceleration along jet in FR I
- Several different acceleration mechanisms may be involved
 - X-ray emission is not all concentrated at shocks, so shock acceleration is not the whole story
 - but is still likely to play a role
 - stochastic (Fermi 2nd order) acceleration in turbulent fields may be implicated—would yield required diffuse X-ray emission
 - magnetic reconnection may also occur
- AGN are not ruled out as the source of UHE CRs, but neither are they definitely ruled in

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Nearby AGN




M87
17 Mpc

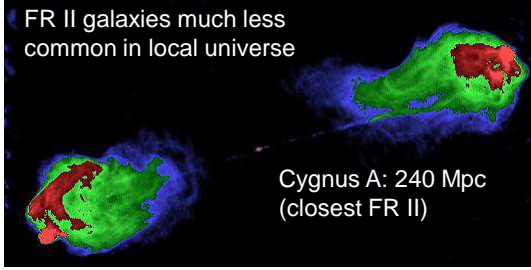


4 arcmin

Cen A and M87 likely to dominate UHE CR flux because of GZK cutoff



Centaurus A (NGC 5128): 3.7 Mpc

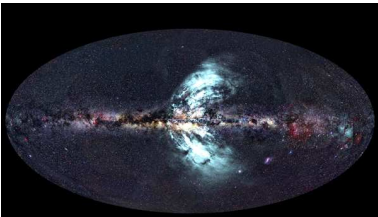


FR II galaxies much less common in local universe

Cygnus A: 240 Mpc (closest FR II)

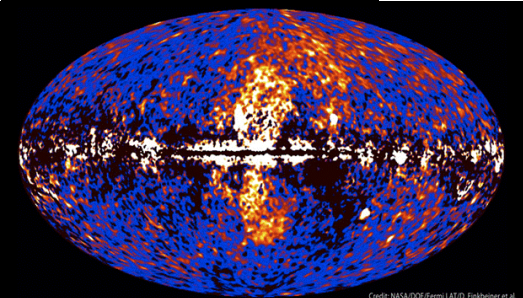
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Our Galaxy as an AGN



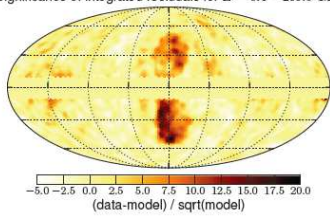
“Bubbles” seen in γ -rays, microwave and radio

Relic of Sgr A* activity $\sim 10^7$ yr ago?

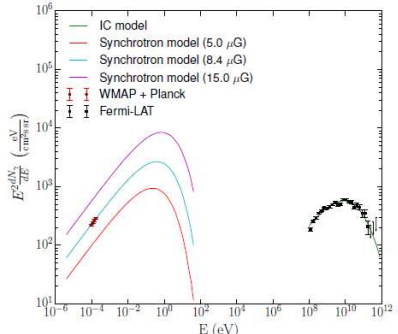


Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

Significance of integrated residuals for $E = 6.4 - 289.6$ GeV



-5.0 -2.5 0.0 2.5 5.0 7.5 10.0 12.5 15.0 17.5 20.0
(data-model) / sqrt(model)



$F^{>E} \frac{dN}{dE dt dA d\Omega}$ (cm⁻² s⁻¹ sr⁻¹ GeV⁻¹) vs E (eV)

- IC model
- Synchrotron model (5.0 μ G)
- Synchrotron model (8.4 μ G)
- Synchrotron model (15.0 μ G)
- WMAP + Planck
- Fermi-LAT

Summary

You should read chapter 4 of the notes (in progress)

You should know about

- *supernova remnants*
 - *pulsar wind nebulae*
 - *gamma-ray bursts*
 - *active galactic nuclei*
- Explaining the observed cosmic ray spectrum requires both Galactic and extragalactic sources
 - Galactic sources explain spectrum up to the “knee”, extragalactic beyond this
 - Supernova remnants strongly believed responsible for Galactic emission
 - energetics OK, some observed spectra show evidence for π^0 decay
 - properties are consistent with diffusive shock acceleration
 - Pulsar wind nebulae dominate high-energy photon emission—unclear whether these accelerate hadrons
 - probably *not* DSA in this case: magnetic reconnection or (if only leptons) resonant cyclotron absorption
 - Main extragalactic sources are GRBs and radio-loud AGN
 - GRBs contain highly relativistic shocks
 - Lack of detected neutrino emission not definitive yet but interesting
 - Radio-loud AGN have relativistic bulk motion with shocks
 - distributed X-ray emission suggests acceleration not all localised to shocks—Fermi 2nd order and/or magnetic reconnection may be relevant