Unsolved Problems in Plasma Astrophysics

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PPPL 50th Anniversary Celebration
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Some unsolved problems

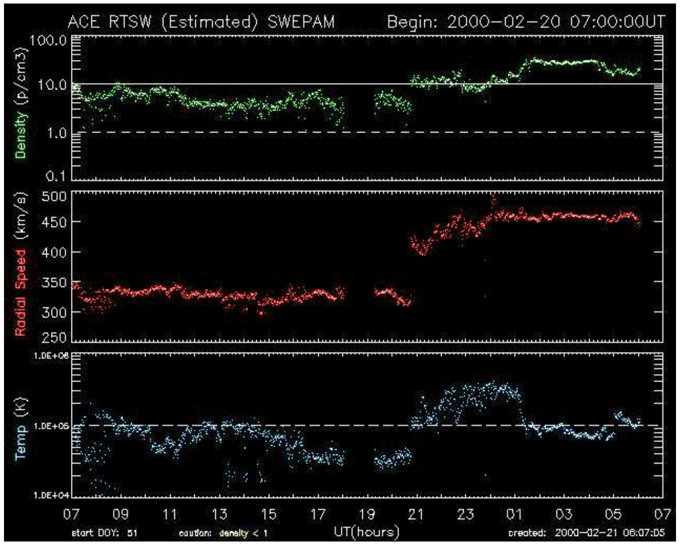
Name	Age
Magnetic Dynamo	*Larmor* 1919
Magnetic Reconnection	*Giovanelli* 1947
Accretion Disks	*von Weizsäcker* 1943
Collisionless Shocks	*Ness et al.* 1964
Astrophysical Jets	*Shlovskii* 1955
Cosmic-Ray Acceleration	*Fermi* 1949
Interstellar Turbulence	*Scheuer* 1968
Pulsar Emission	*Pacini* 1967

Collisionless shocks

- What is the division of postshock energy among ions, electrons, cosmic rays, and magnetic field?
- What processes mediate the shock?

Planetary bow shocks:

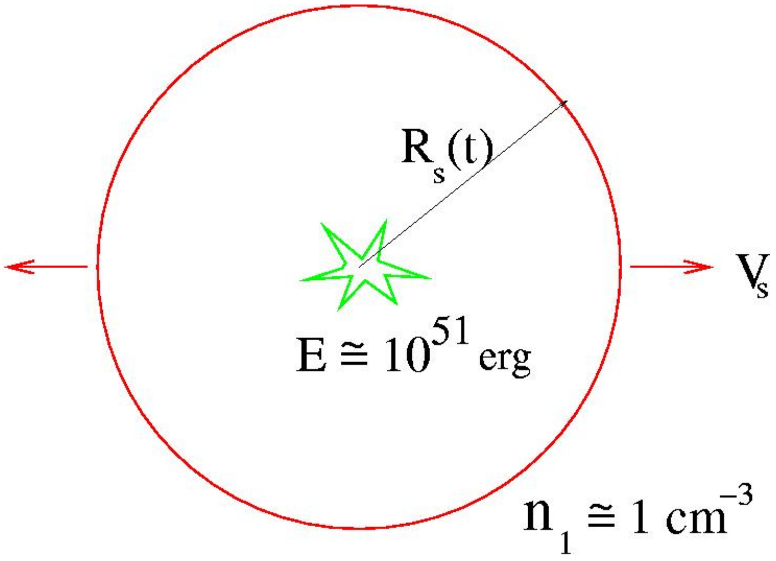
- $M_A \equiv V_{\mathsf{sh}}/V_{\mathsf{A}} \sim 5 - 20$
- $\Delta T_e \approx (0.1 - 0.3)\Delta T_e$
- $L_{\mathsf{sh}} \sim r_{g,i}$



Shock passage 2/20/02

(NASA/ACE)

Supernova remnants/shocks



$$V_s(t) \approx 0.35 \left(\frac{E}{m_p n}\right)^{1/5} t^{-3/5}$$

$$\approx 1600\,(t/10^3\mathrm{yr})^{-3/5}\,\mathrm{km\,s^{-1}}$$

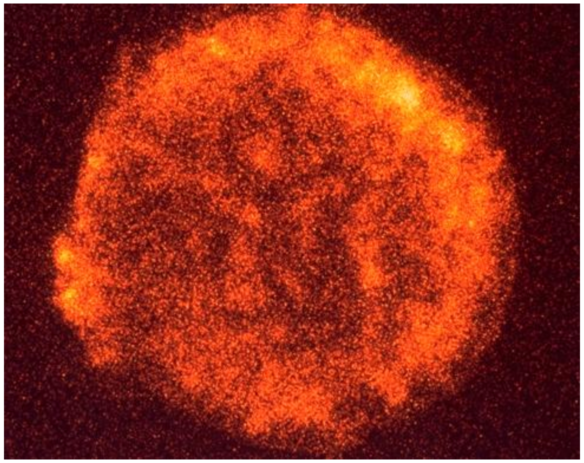
$$k_\mathrm{B}\bar{T}_2 \approx \frac{3}{16}\mu m_p V_s^2$$

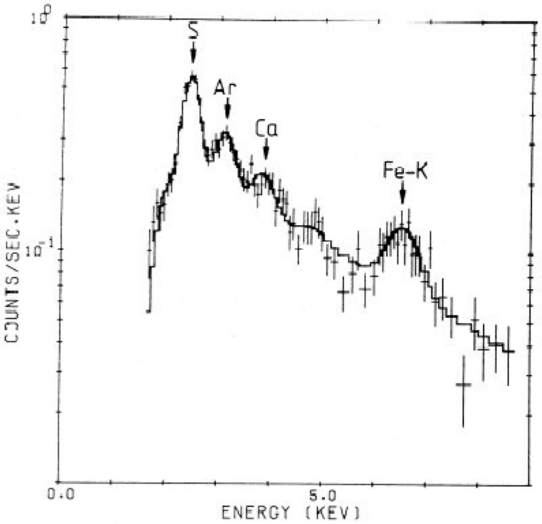
$$\approx 3.\,(t/10^3\mathrm{yr})^{-6/5}\,\mathrm{keV}.$$

Collisional equilibration $\Rightarrow \frac{T_e}{T_p} \approx 0.4\,(t/10^3\mathrm{yr})^{28/25}$

Tycho

Exploded 1572 AD ⇒ $t = 429\,\mathrm{yr}$





	Observed	Predicted*
V_s $[\mathrm{km\,s^{-1}}]$	2600 ± 260†	1870
$\bar{T}_2$ [keV]	?	4.2
$T_{e,2}$ [keV]	5 ± 0.5	1.6

*For $n = 1.13$ & $E = 2 \times 10^{50}$ (Smith et al. 1988)

†From radio, if $D = 2.3\,\mathrm{kpc}$ (Strom et al. 1982)

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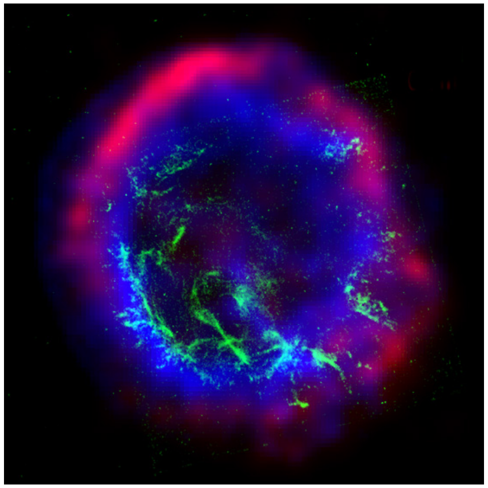
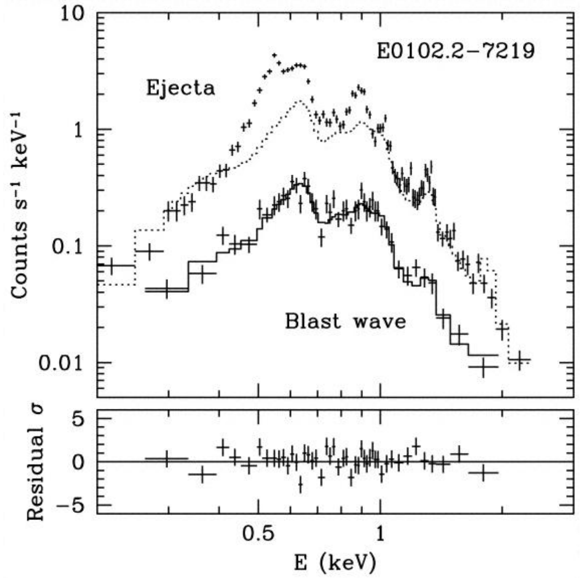


[ACTA/Chandra/HST]

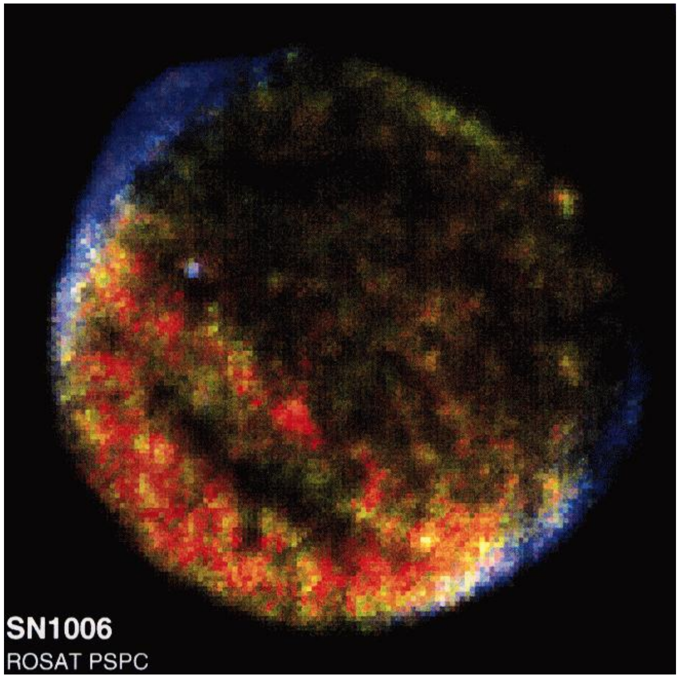


	Observed*	Predicted*
V_s [$\mathrm{km\,s^{-1}}$]	6200 ± 1600	*free expansion ?*
$\bar{T}_2$ [keV]	?	$45 \pm 25^{\dagger}$
$T_{e,2}$ [keV]	0.78 ± 0.16	$\gtrsim 4.5$

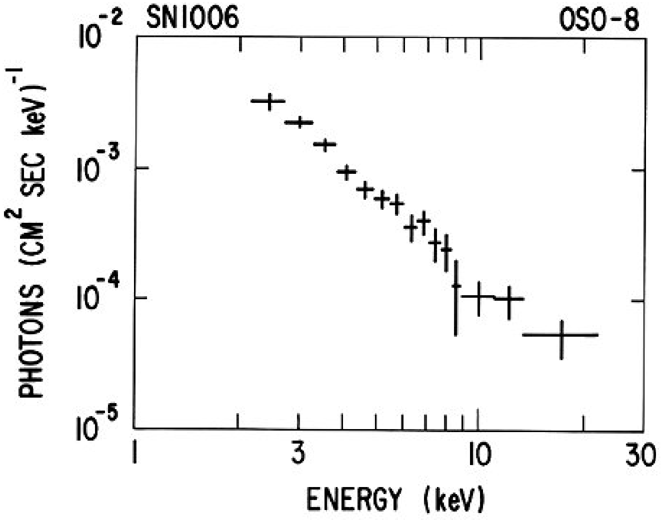
*Hughes et al. 2000, ApJ, 543, L61

† based on V_s observed

SN 1006



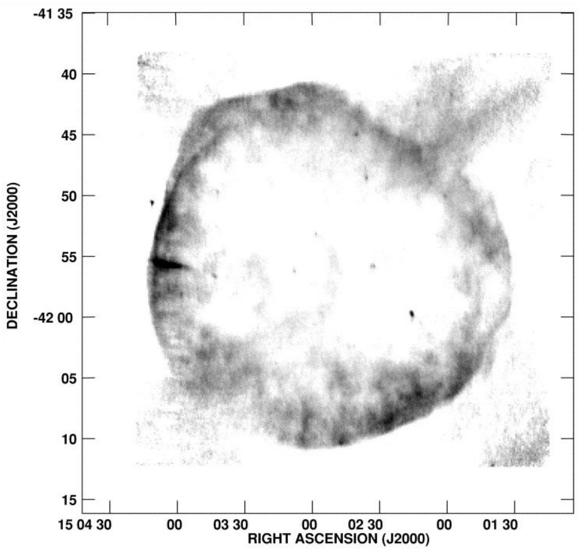
X-ray image (ROSAT)



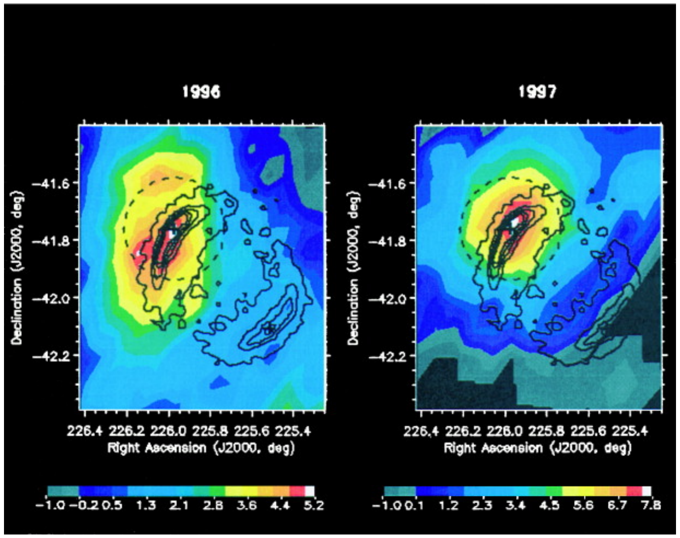
Hard-X-ray spectrum (OSO-8)

- Thermal component: $kT_e \approx 0.6\,\mathrm{keV}$ (1.3 keV predicted)
- Nonthermal X-rays dominate, seen mainly in rims
- Synchrotron model favored, with electrons up to $\sim 100\,\mathrm{TeV}$!

SN1006 in radio & gamma rays



Radio image (VLA)



TeV significance [color] (CANGAROO)

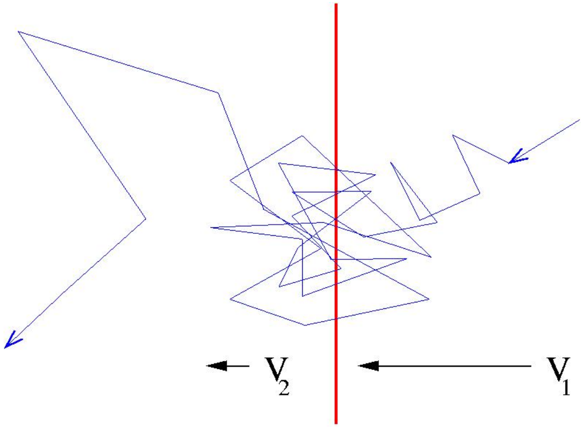
$$\hbar\omega_{\rm sync} \approx \gamma_e^2\,\hbar\omega_{\rm cyc} \approx 4\,{\rm keV}\left(\frac{\mathcal{E}_e}{100{\rm TeV}}\right)^2\left(\frac{B}{9\mu{\rm G}}\right)$$

$$\hbar\omega_{\rm IC} \approx \gamma_e^2\,\mathcal{E}_{\rm CMB} \approx 30\,{\rm TeV}\left(\frac{\mathcal{E}_e}{100{\rm TeV}}\right)^2\left(\frac{T_{\rm CMB}}{2.73{\rm K}}\right)$$

1^{st}-order Fermi acceleration

$n = \frac{\text{particles}}{\text{volume}}$ downstream; $r = \frac{V_1}{V_2}$ =shock compression ratio.

Energy gain δ & escape probability P per shock crossing:



$$\delta \equiv \left\langle \frac{\Delta\mathcal{E}}{\mathcal{E}} \right\rangle = \frac{4}{3c}|V_1 - V_2| << 1$$

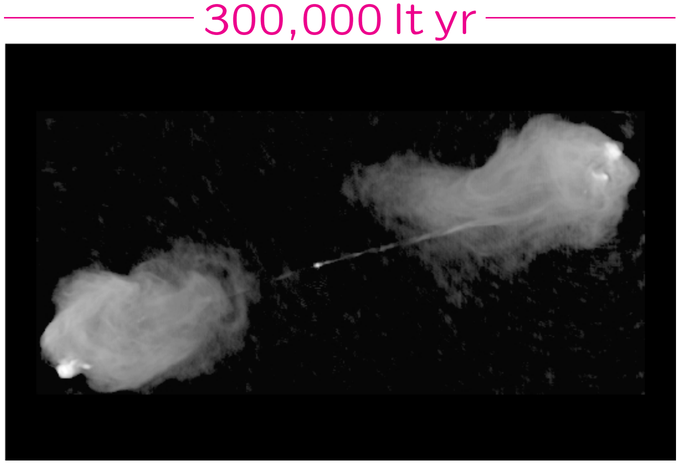
$$P \approx \frac{\text{net flux}}{\text{upcrossing flux}} = \frac{n|V_2|}{nc/4} = \frac{3\delta}{r-1}$$

k crossings : $\langle n(\geq k)\rangle = n_0\,(1-P)^k, \quad \langle \mathcal{E}_k \rangle = \mathcal{E}_0\,(1+\delta)^k$

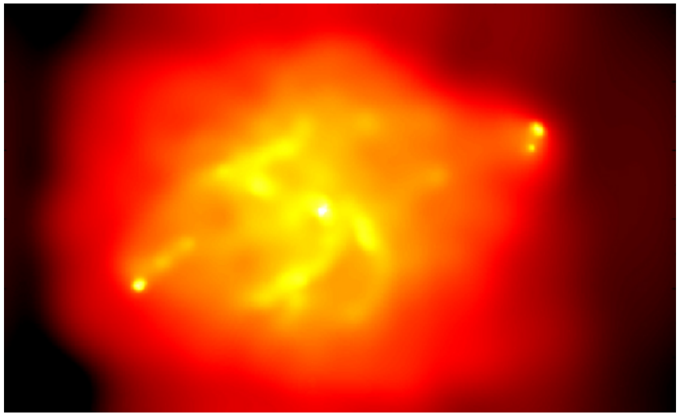
$n(\geq \mathcal{E}) \propto \mathcal{E}^{-3/(r-1)} \;\rightarrow\; \mathcal{E}^{-1}$ for $r = 4$.

Relativistic shocks: $\mathcal{E}^{-1.23}$ *[Kirk et al. 2000]*

Extragalactic radio jets



Cygnus A at 5 GHz (VLA)



. . . & X-rays (Chandra)

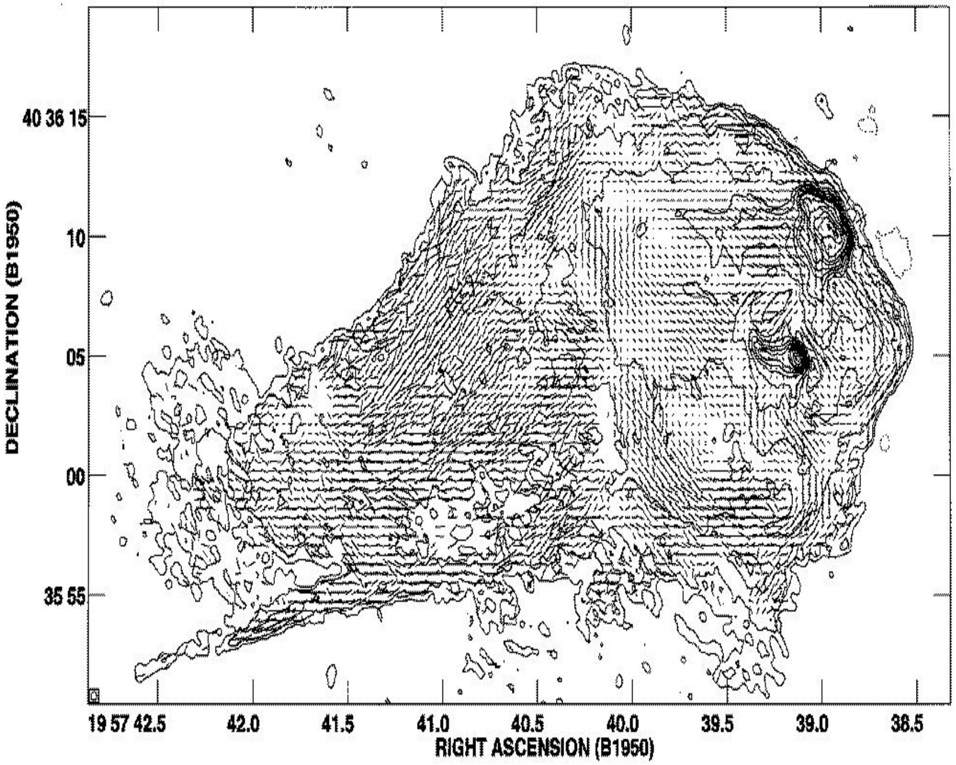
- Observed radio synchrotron $L_\nu \propto P_e P_B^{3/4}$
  $\Rightarrow P \geq P_B + P_e \geq 3 \times 10^{-9}\,\mathrm{dyn\,cm^{-2}}$ in hot spot

- SSC X-rays $\Rightarrow B \geq 150\,\mu\mathrm{G}$ $\sim B_{\mathrm{eq}}$

- Pressure balance of lobes & IGM $\Rightarrow P_i \sim 10(P_e + P_B)$

Cygnus A, continued

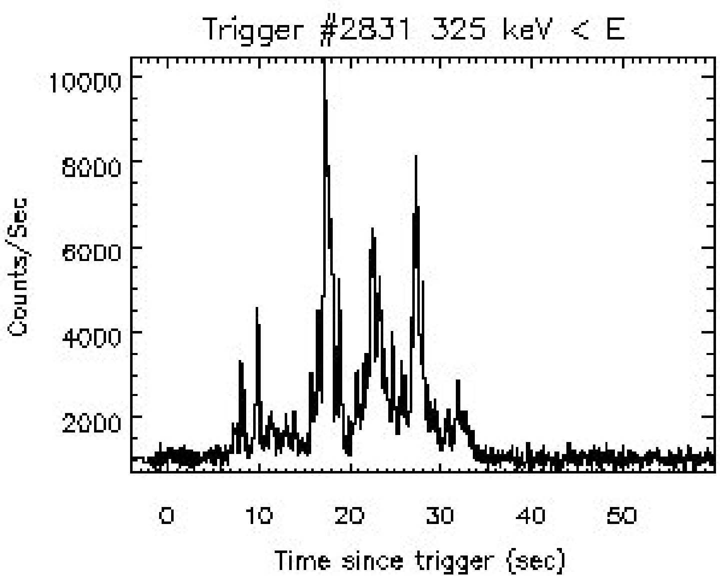
- $P_{\text{min}}^{\text{spot}} \lesssim 10 P_{\text{min}}^{\text{jet}}$
  $\Rightarrow M \lesssim \sqrt{10}$
- Well-ordered field seen



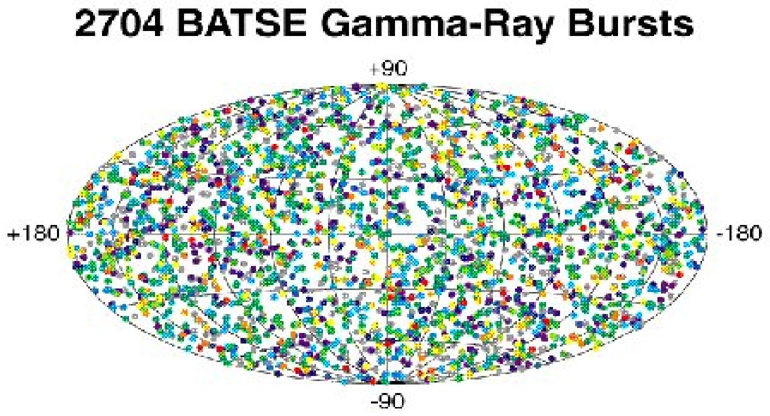
Polarization in N$^{\text{rn}}$ *lobe, 6 GHz*

$\Rightarrow$ Not much field amplification in shock

Gamma-Ray Bursts

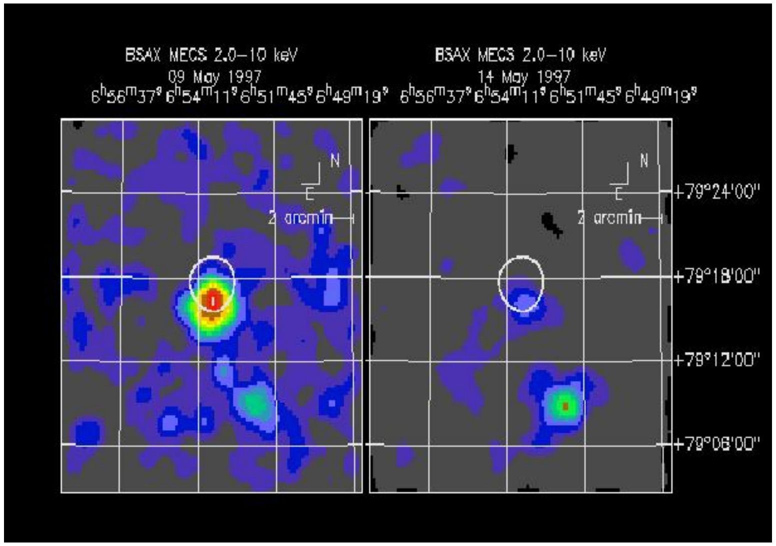


A typical GRB (BATSE/GRO)

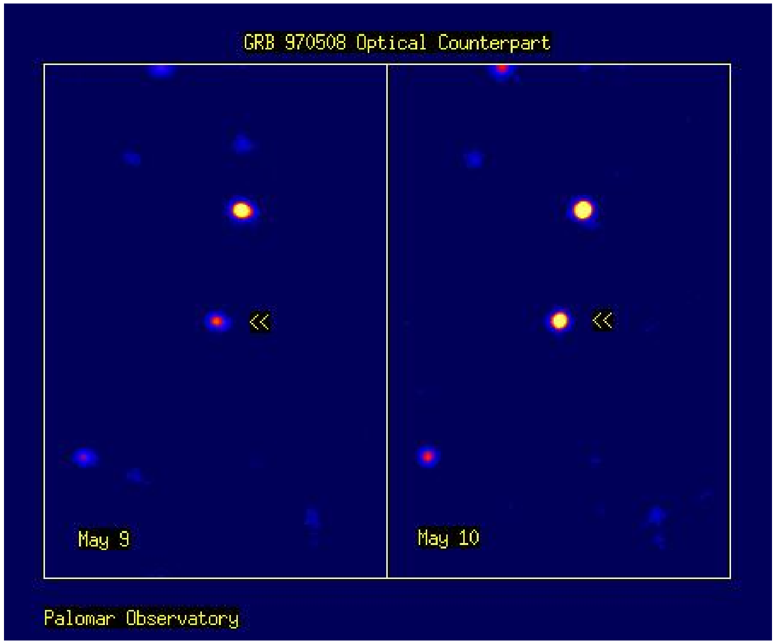


Isotropic sky distribution of GRBs

GRB Afterglows

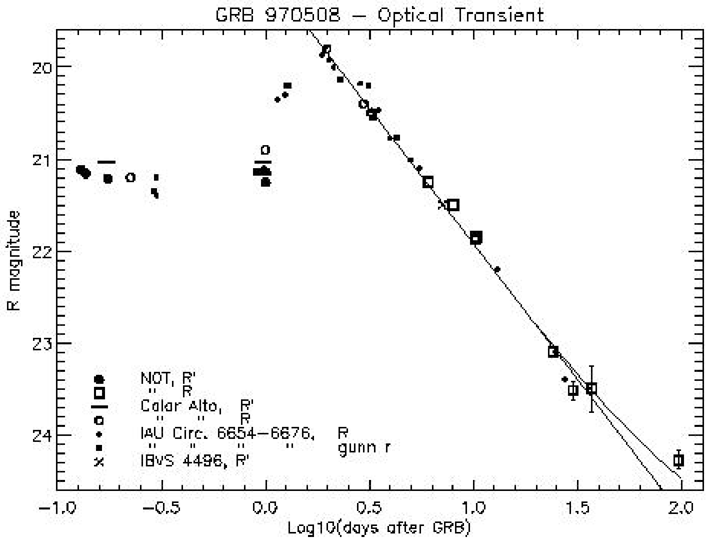


X-ray afterglow of GRB970508
(Beppo-SAX)

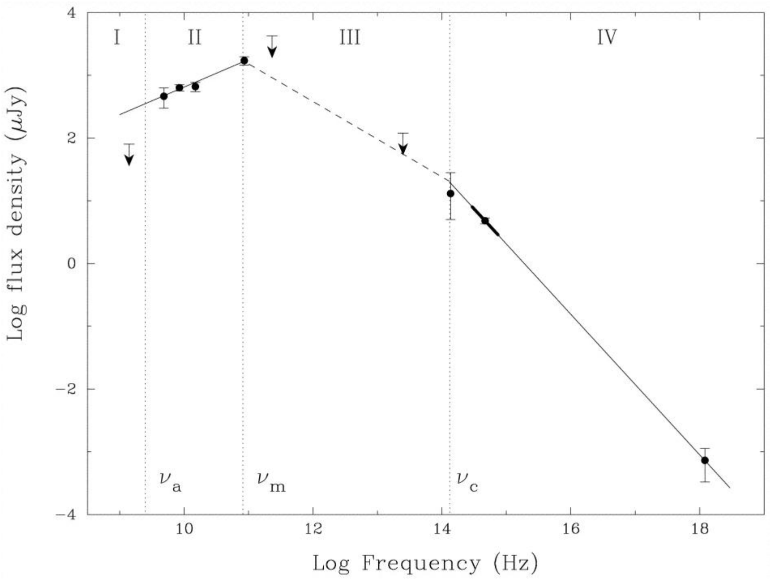


Optical afterglow of GRB970508
(Djorgovski/Palomar)

GRB Afterglows, continued



Optical lightcurve of GRB970508 (*Pedersen*)



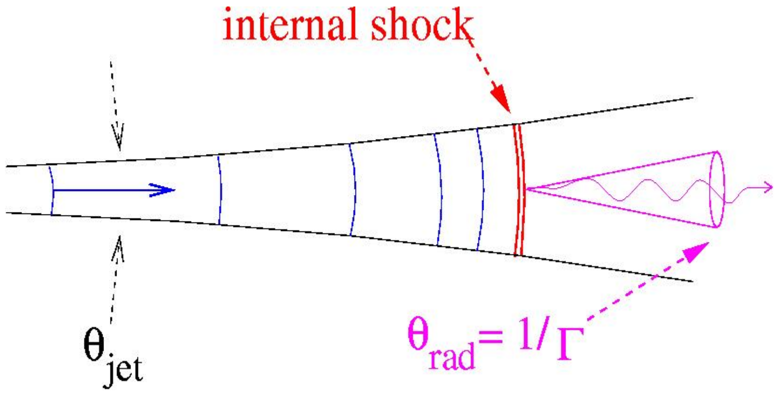
Radio-to-X-ray spectrum two weeks after burst (Galama et al. 1998*)*

GRB inferences

1. Cosmological distance $D \sim 10^{10}\,\mathrm{lt\,yr}$
   - Isotropic distribution
   - afterglow redshifts $z \gtrsim 1$
2. Highly energetic: $dE_{\mathrm{burst}}/d\Omega = D^2 F \sim 10^{51}\,\mathrm{erg\ sr}^{-1}$
3. Relativistic source: $\Gamma_{\mathrm{src}} \equiv \left[1 - (V_{\mathrm{src}}/c)^2\right]^{-1/2} \gtrsim 10^2$.
   - Optical depth for $\gamma\gamma \to e^+e^-$ in <u>stationary</u> source is

$$\tau_{\mathrm{pair}} \sim \frac{\sigma_{\mathrm{T}} \dot{E}_\gamma}{m_e c^4 \Delta t} \gtrsim 10^{12}$$

GRB Standard Model



- Unsteady relativistic jet, $E_{\rm j} \gtrsim 10^{50}\,{\rm erg}$
- Variable Lorentz factor $\Gamma_{\rm j} = \dot{E}_{\rm j}/\dot{M}_{\rm j}c^2 \gtrsim 300$
- Fast ejecta overtake slower; kinetic $\Rightarrow$ internal energy
- Synchrotron/IC emission; photon energy $< m_ec^2$ in rest frame
- Net radiative efficiency $\lesssim 20\%$
- Postshock magnetic energy $\sim$ equipartition value

GRB Afterglow Model

Relativistic version of Sedov sol$^{\text{n}}$:

$$
\begin{aligned}
\text{swept-up mass } M(t) &\approx \frac{4\pi}{3} m_p n_{\text{ext}} R_{\text{s}}^3 \gg M_{\text{ejecta}} \\
\text{adiabatic evolution } E &\propto M\Gamma_{\text{s}}^2 \approx \text{constant} \\
t_{\text{emit}} &\approx \frac{R_{\text{s}}}{c}, \qquad (\Gamma_{\text{s}} \gg 1) \\
t_{\text{obs}} &\approx \int \left(1 - \frac{\text{V}_{\text{s}}}{c}\right) dt_{\text{em}} \propto t_{\text{emit}}/\Gamma_{\text{s}}^2 \\
\Rightarrow \quad \Gamma_{\text{s}} &\sim \left(\frac{E}{\rho_{\text{ext}}}\right)^{1/8} t_{\text{obs}}^{-3/8} \approx 600 \left(\frac{E_{51}}{n_0}\right)^{1/8} t_{\text{sec}}^{-3/8} .
\end{aligned}
$$

Model for Afterglow Emission

Assumptions:

- Adiabatic relativistic blastwave/jet (as above)
- Synchrotron emission
- Fixed fractions $\epsilon_e \,\&\, \epsilon_B$ of postshock energy in $e^{\pm}$ & field
- $N_{e^{\pm}}(\mathcal{E}) \propto \mathcal{E}^{-p}$, $\mathcal{E} \geq \mathcal{E}_{\text{min}}$, $p \gtrsim 2$
- $\mathcal{E}_{\text{min}} \propto \Gamma_s(t)$ in shock frame

Predictions:

$$F_\nu \propto \epsilon_e \epsilon_B^{1/2} n_0 E_0 \quad \times \quad \begin{cases} (\nu/\nu_{\text{min}})^{1/3} & \nu < \nu_{\text{min}} \\ (\nu/\nu_{\text{min}})^{-(p-1)/2} & \nu_{\text{cool}} > \nu > \nu_{\text{min}} \\ (\nu_{\text{cool}}/\nu_{\text{min}})^{1/2} (\nu/\nu_{\text{min}})^{-p/2} & \nu > \nu_{\text{cool}} \end{cases}$$

$$\nu_{\text{min}} \propto \Gamma_{\text{s}}^4 n_0^{1/2} \epsilon_B^{1/2} \propto t^{-3/2}$$

How is B made in afterglow shocks?

- Compressed pre-shock field is inadequate

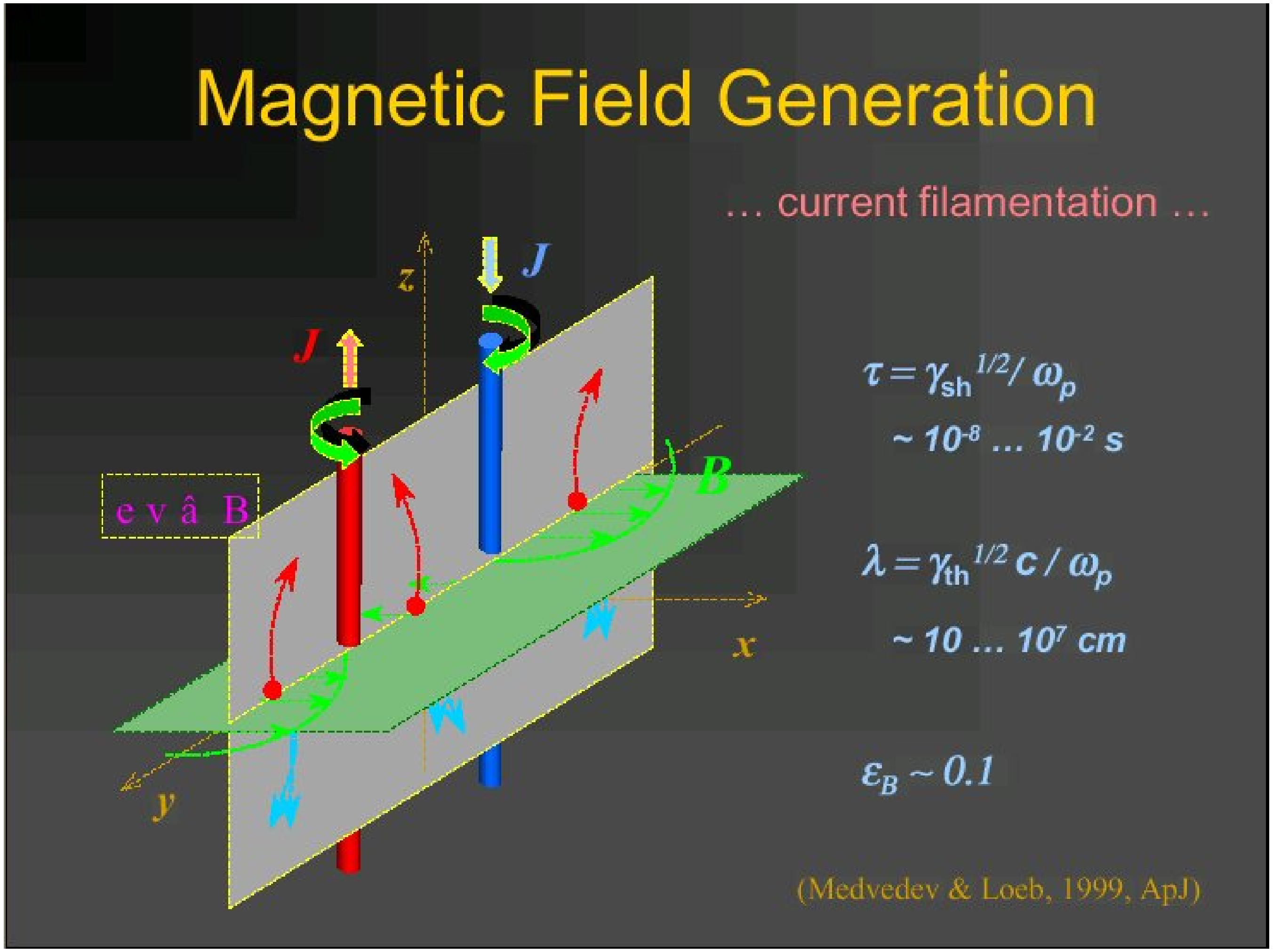
$$\bar{\epsilon}_{B,\text{shock}} \lesssim 3\epsilon_{B,ISM} = 3\left(\frac{V_A}{c}\right)^2 \sim 10^{-8}$$

- Pre-shock inhomogeneity ⇒ Postshock vorticity ⇒ Dynamo (?)

- Weibel (1959) instability *[Medvedev & Loeb 1999]*
  - Magnetic two-stream instability; $t_{\text{growth}} \sim \omega_{pe}^{-1}$
  - $\epsilon_B \sim 10^{-3} - 10^{-1}$ in simulations*
  - Does B persist $(t \gg \omega_p^{-1})$? *[Gruzinov 2000]*
  - Why doesn't this operate in supernovae?

**None published with counterstreaming relativistic* e *&* p *in 3D*

Weibel mechanism



Magnetic Field Generation

… current filamentation …

$\tau = \gamma_{sh}^{1/2} / \omega_p$

$\sim 10^{-8} \ldots 10^{-2}$ s

$\lambda = \gamma_{th}^{1/2} c / \omega_p$

$\sim 10 \ldots 10^{7}$ cm

$\varepsilon_B \sim 0.1$

(Medvedev & Loeb, 1999, ApJ)

Medvedev 2002

Summary

- Fast ($M_A \gg 1$) collisionless shocks occur in supernova blast waves, pulsar winds, radio jets, GRBs & afterglows
- Postshock relativistic electrons are seen (*via* synchrotron), & their energy spectrum is calculable (with assumptions)
- Not much evidence for dynamo action in nonrelativistic shocks, But gamma-ray bursts and afterglows require it
- Collisionless (Weibel? instability is promising, needs work
    - Does field persist, and at what level?
    - Do ions contribute to field growth?
    - Do electrons reach equipartion?
    - Are relativistic effects essential?