Comparing the particle acceleration rates of different astrophysical environments

F. Catapano, *A. Greco, G. Zimbardo, S. Perri, A. Retino*

Acceleration rates from observations

Event Name	ΔE	Δt	$\Delta E/\Delta t$
Solar Flares ,GLE:			
protons	> 13 GeV	2min	183 MeV/s
electrons	10-100 MeV	< 0.1 s	100-10000 MeV/s
Crab Nebula Flares:			
September 2010	$1.5 \cdot 10^{15}$ eV	24 hr	14 GeV/s
April 2011	$3 \cdot 10^{15}$ eV	6-10 hr	113 GeV/s
Magnetotail:			
electrons	~ 100 KeV	5 s	20 KeV/s
protons	100-500 KeV	20 s	5-25 KeV/s
SNR shocks:			
SN 1006	10^{15} eV	1000 years	30 KeV/s
Tycho	$5 \cdot 10^{14}$ eV	400 years	40 KeV/s
Heliospheric shocks:			
1 AU (ACE)	1 MeV	2 days	6 eV/s
5 AU (Ulysses)	5 MeV	10 days	6 eV/s

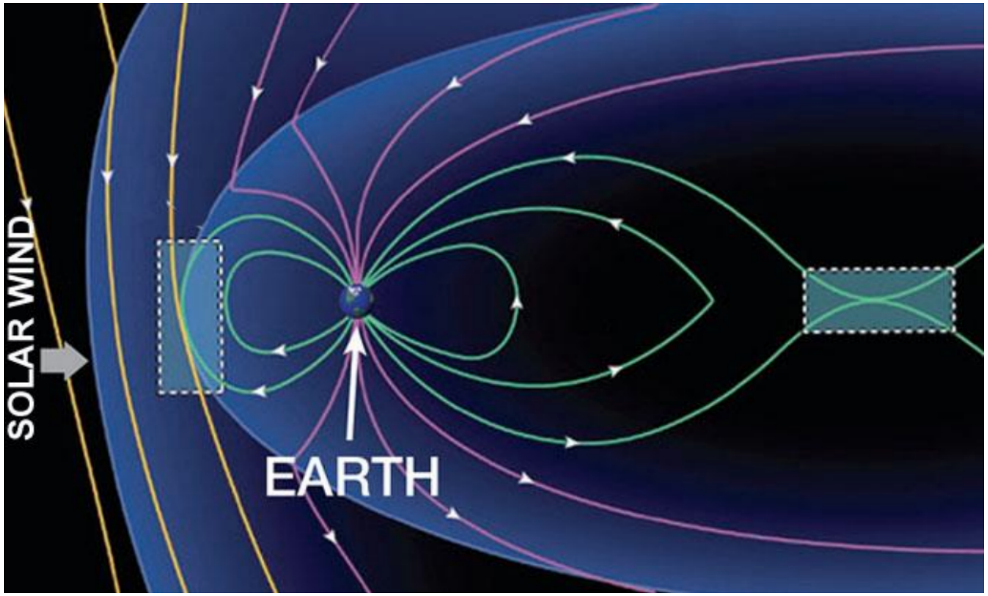
$\Delta E/\Delta t$
260 MeV/s 10 GeV/s
22 GeV/s
0.5 keV/s 4 kev/s

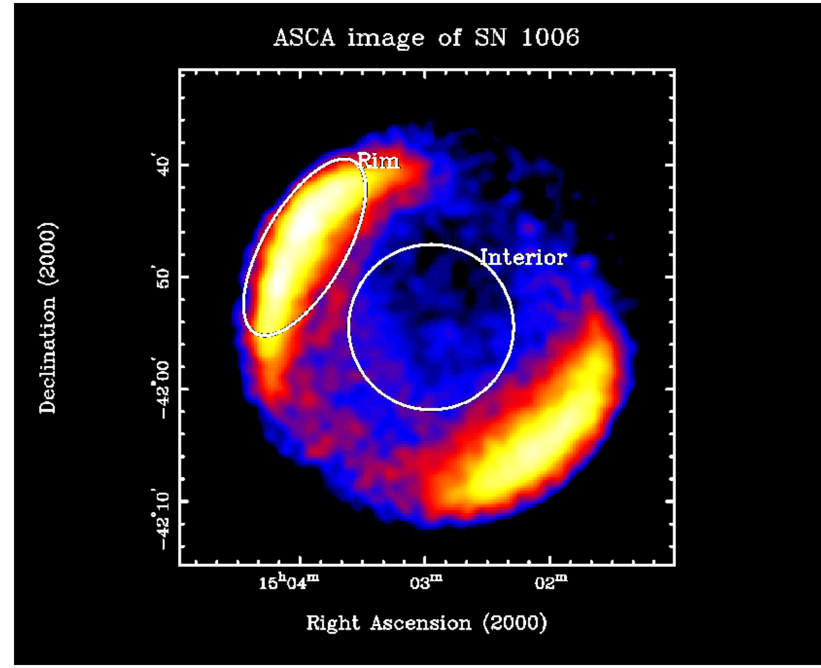
Magnetic reconnection can explain the acceleration rates observed in solar flares, Crab flares, and energetic protons in the Earth's magnetotail.

$$\frac{\Delta E}{\Delta t} = q B V \nu$$

Shock acceleration :
DSA vs SSA ?

Shock acceleration is generally slower and requires magnetic field amplification in the SNR environment and anomalous transport at heliospheric shocks.





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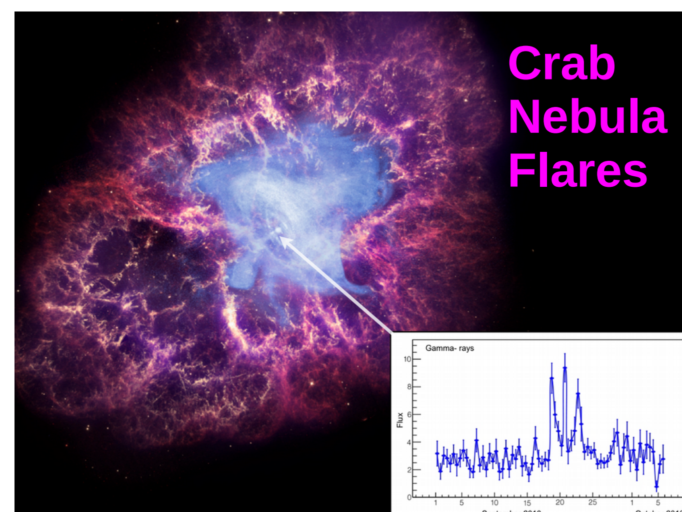


Tab1 Acceleration rates from observations

Event Name	ΔE	Δt	$\Delta E/\Delta t$	References
Solar Flares ,GLE:				
protons	> 13 GeV	2min	183 MeV/s	1
electrons	10-100 MeV	< 0.1 s	100-10000 MeV/s	2
Crab Nebula Flares:				
September 2010	$1.5 \cdot 10^{15}$ eV	24 hr	14 GeV/s	3
April 2011	$3 \cdot 10^{15}$ eV	6-10 hr	113 GeV/s	4
Magnetotail:				
electrons	~ 100 KeV	5 s	20 KeV/s	5
protons	100-500 KeV	20 s	5-25 KeV/s	6
SNR shocks:				
SN 1006	10^{15} eV	1000 years	30 KeV/s	7
Tycho	$5 \cdot 10^{14}$ eV	400 years	40 KeV/s	8
Heliospheric shocks:				
1 AU (ACE)	1 MeV	2 days	6 eV/s	9
5 AU (Ulysses)	5 MeV	10 days	6 eV/s	10, 11

References. (1) McCracken et al. (2016); (2) Raymond et al. (2012); (3) Taviani et al. (2011); (4) Striani et al. (2011); (5) Imada et al. (2007); (6) Birn et al. (2012); (7) Amato (2014); (8) Morlino and Caprioli (2012); (9) Perri and Zimbardo (2015); (10) Desai et al. (1997); (11) Perri and Zimbardo (2008).

Observed events have been considered in order to extrapolate the acceleration rates.

The values of $\Delta E/\Delta t$ are different among the different environments, It means that various mechanisms produce such energetic particles.

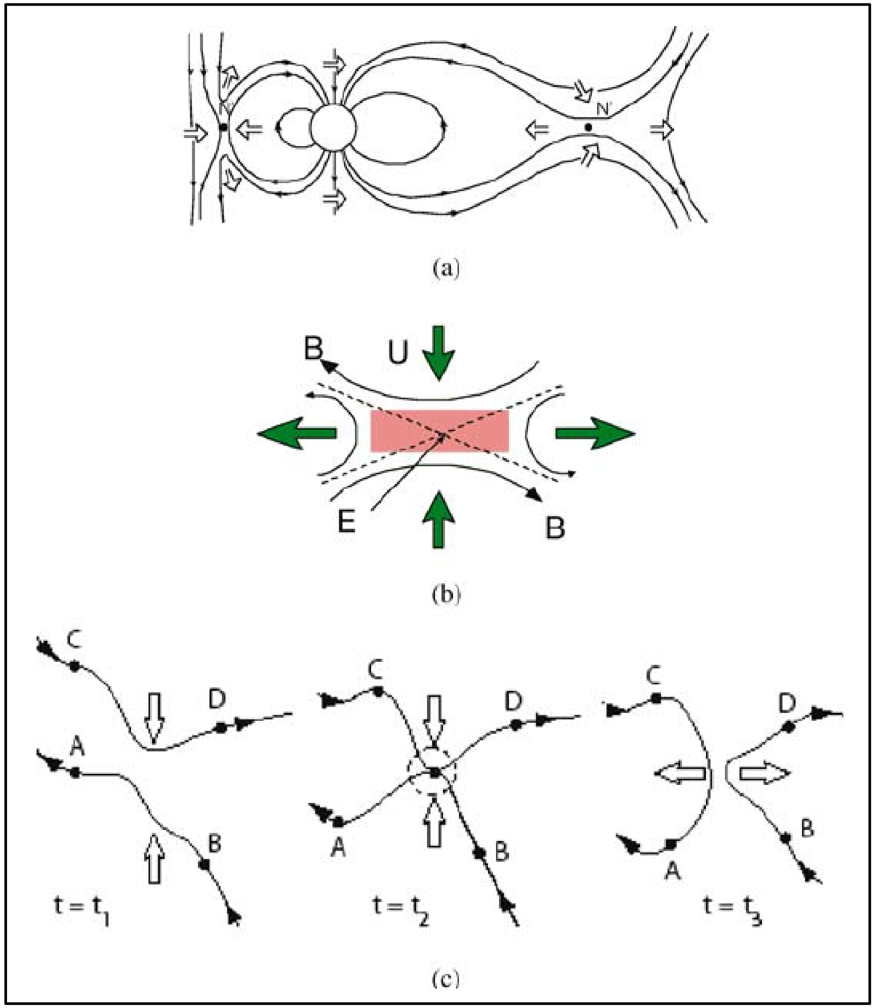
But, is possible to find a common acceleration mechanism?

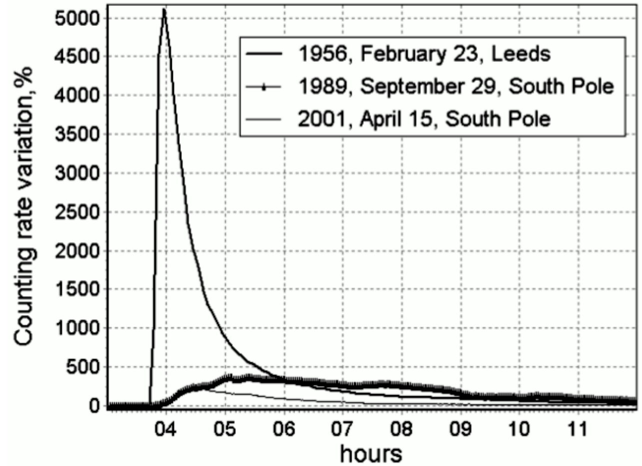
If yes, how it depend on the typical features of the environments?

Magnetic reconnection & shock acceleration

We consider this two acceleration mechanisms and we applied it at the considered astrophysical environments.

On magnetic reconnection...

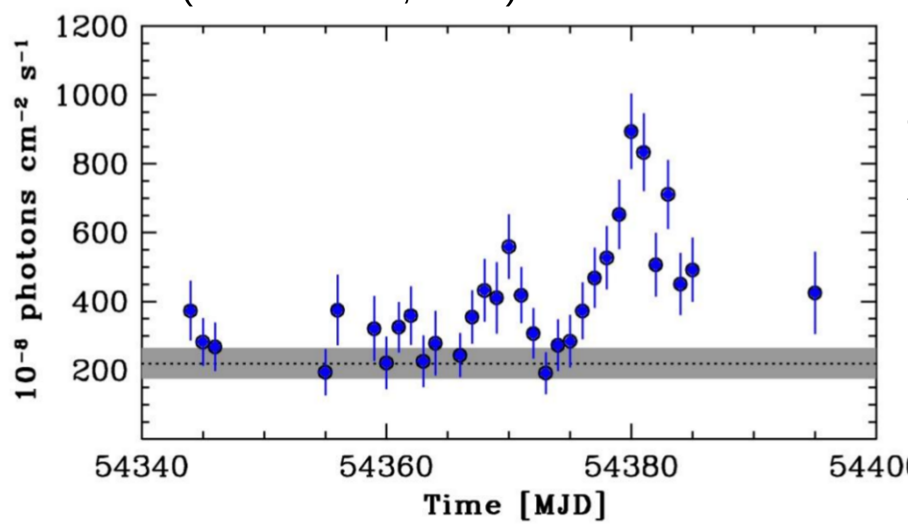




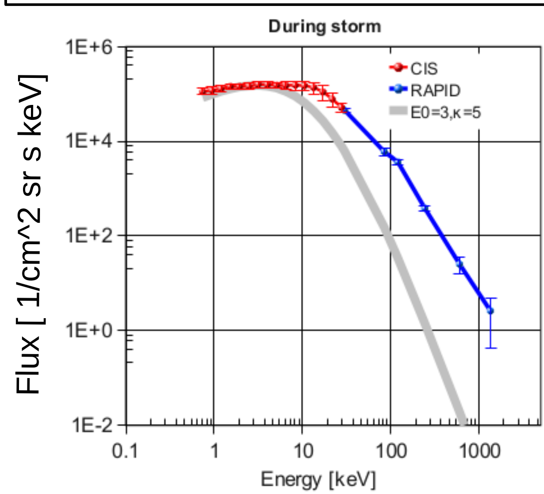
Ground Level Event: 13 GeV protons accelerated in the solar corona in less than 2 min.

(McCracken et al., 2016)

(Taviani et al., 2011)



Crab Nebula flares, from AGILE observations : ele. 10^{15} eV in few hours.



Supra-thermal ions observed in the Earth's magnetotail during a Storm. Energies up to 1 MeV in few days.

(Haaland et al., 2011)

On magnetic reconnection...

$$W = q\,\delta E\,\Delta s \rightarrow \nu = \Delta s/\Delta t, \quad \delta E \sim V B \rightarrow \frac{\Delta E}{\Delta t} = q B V \nu$$

Tab2

Event Name	Parameters	$\Delta E/\Delta t$	References
			2
Solar Flares ,GLE:			
protons	B=10 G, V=2000 km/s, $v_p = 130$ km/s	260 MeV/s	12
electrons	$v_e = 5000$ km/s	10 GeV/s	13
Crab Nebula Flares:	B=5 mG, V= 0.5 c, $v_e = c$	22 GeV/s	14, 15
Magnetotail:			
DF	B=20 nT, ν=500 km/s, $v_p = 50$ km/s	0.5 keV/s	16
e.m. fluctuations	B=10 nT, V=400 km/s, $v_p = 400$ km/s	4 kev/s	17

From Tab1

$\Delta E/\Delta t$
183 MeV/s 100-10000 MeV/s
14 GeV/s 113 GeV/s
5-25 KeV/s

References. (12) Raymond et al. (2012) ,(13), (14) Baty et al. (2013), (15) Cerutti et al. (2012, 2013), (16) Greco et al. (2015), (17) Catapano et al. (2016)

We find that magnetic reconnection can explain the acceleration rates observed both in solar flares and Crab flares, as well as for energetic protons in the Earth's magnetotail.

On shock acceleration...

Composite view of SN 1006:
- X-ray in blue,
- optical in yellowish hues,
- radio image data in red.

Non-thermal synchrotron X-rays from the 30 arc-min shell indicate high-energy electrons in shock front.

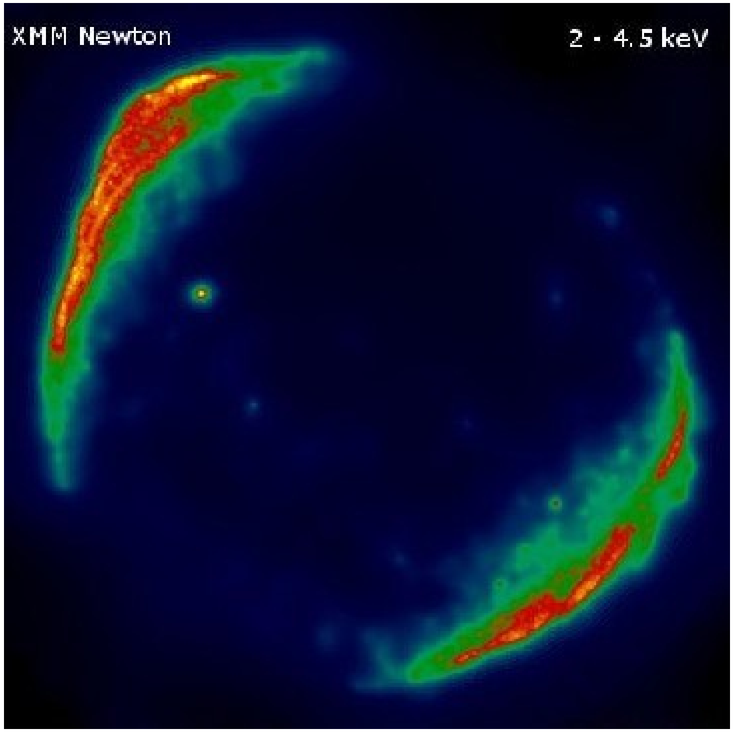
Signals from the N-E and S-W rim were detected with a significance of over 5 sigma.

The morphology of the gamma ray source is similar to the X-ray source (above).

The morphology of SN 1006 and X-rays and gamma rays can be explained as due to the interstellar magnetic field threading N-E to S-W.

Efficient particle acceleration is in the regions of parallel shock front.

(Naumann-Godo et al., H.E.S.S. collaboration, 2008)



On shock acceleration...

Anomalous transport is characterized by:

$$\langle \Delta x^2 \rangle = 2 D_\alpha t^\alpha \quad \begin{cases} \alpha < 1 & \textit{subdiffusion} \\ 1 < \alpha < 2 & \textit{superdiffusion} \\ \alpha = 2 & \textit{ballistic regimes} \end{cases}$$

Acceleration times predicted by DSA turn out to be much longer than necessary to explain the observations. DSA has been extended to the case of anomalous transport, giving rise to SSA.

Diffusive Shock Acceleration **DSA** vs Superdiffusive Shock Acceleration **SSA**

$$t_{acc}^{DSA} = \frac{3}{V_1 - V_2} \left(\frac{D_{1x}}{V_1} + \frac{D_{2x}}{V_2} \right)$$

, where

$$D_x \sim D_{par} \cos^2(\theta_{Bn})$$

and

$$D_{par} = \frac{1}{3} \lambda_{par} v$$

$$t_{acc}^{DSA} \sim \frac{1}{V_1 - V_2} \left(\frac{v}{V_1} \right) \lambda_{par}$$

And equal contribution from downstream.

Lévy walks : power-law distribution of the free path lengths

$$\psi(l,t) \propto |l|^{-\mu+1} \delta(|l| - vt)$$

, with $|l| > l_0$

$$t_{acc}^{SSA} = \frac{3}{V_1 - V_2} \left[\left(\frac{D_{1\alpha x}}{V_1^\alpha} \right)^{1/(2-\alpha)} + \left(\frac{D_{2\alpha x}}{V_2^\alpha} \right)^{1/(2-\alpha)} \right]$$

$$D_\alpha = \frac{2(2-\alpha)}{(3-\alpha)(4-\alpha)} \Gamma(\alpha - 1) l_0^{2-\alpha} v^\alpha$$

$$t_{acc}^{SSA} \sim \frac{1}{V_1 - V_2} \left(\frac{v}{V_1} \right)^{\alpha/(2-\alpha)} l_0$$

On shock acceleration...

Event Name	Energy	$\lambda_{\parallel}$	t^{SSA}	t^{DSA}	$\frac{\Delta E}{\Delta t}^{SSA}$	$\frac{\Delta E}{\Delta t}^{DSA}$	References
Heliospheric shocks:							
ACE 18/02/1999							
(a)	150 keV	0.1 AU	0.4 days	5 days	4 eV/s	0.3 eV/s	18
(b)	400 keV		0.8 days	7 days	6 eV/s	0.7 eV/s	18
ACE 08/06/2000							
(a)	150 keV	0.1 AU	0.3 days	9 days	6 eV/s	0.2 eV/s	18
(b)	400 keV		0.4 days	12 days	12 eV/s	0.4 eV/s	18
Ulysses 12/09/1992	100 keV	1.0 AU	6 days	118 days	0.2 eV/s	0.01 eV/s	18

References. (18) Perri and Zimbardo (2015)

From Tab1

30 KeV/s
40 KeV/s

6 eV/s
6 eV/s

SSA shortens the acceleration times and increases the energy rate with respect to DSA.

The acceleration time in SSA becomes shorter than the typical lifetime of the shock.

Conclusions...

Magnetic reconnection can reproduce the acceleration rates observed in solar flares, Crab nebula flares, as well as for energetic protons in the Earth's magnetotail.

Acceleration times for energetic protons are estimated in the framework of DSA and SSA.
Shorter times are obtained with SSA, but the acceleration rates are smaller than those observed.

The problem of the amplification of the magnetic field at SNRs is still an open issue.

It is possible that, in order to obtain the observed acceleration rates, some process should energize the particles before they undergo SSA (or DSA).