Unfolding of the vortical amplification of the magnetic field at inward shocks of Supernova remnant Cassiopeia A

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International Conference Cosmic Rays 2021

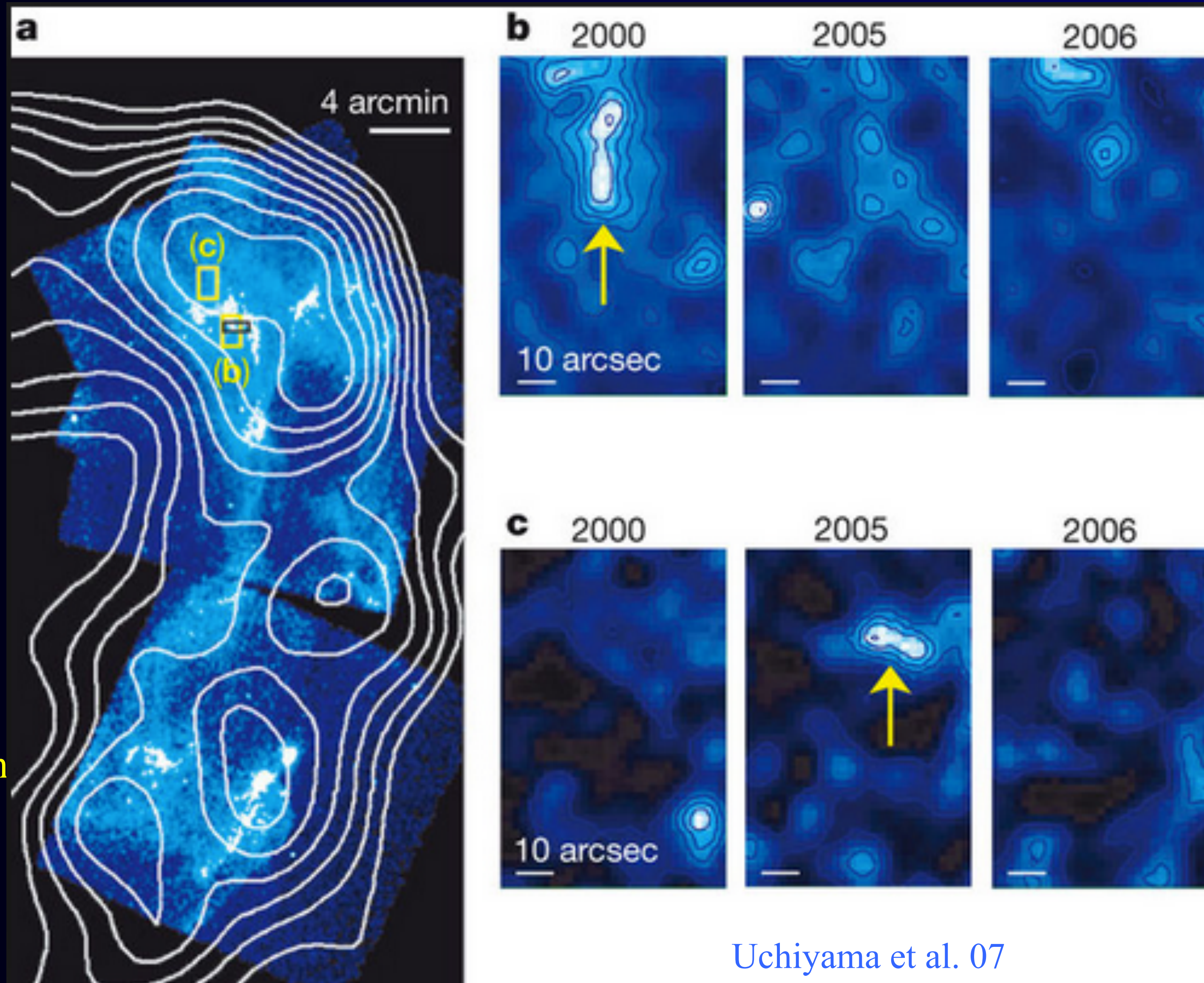
Supernova Remnants: Multi-epoch observations

Case of
RX J1713.7-3946

Chandra:

Bright highly
time-variable
spots ~ 0.01 pc:

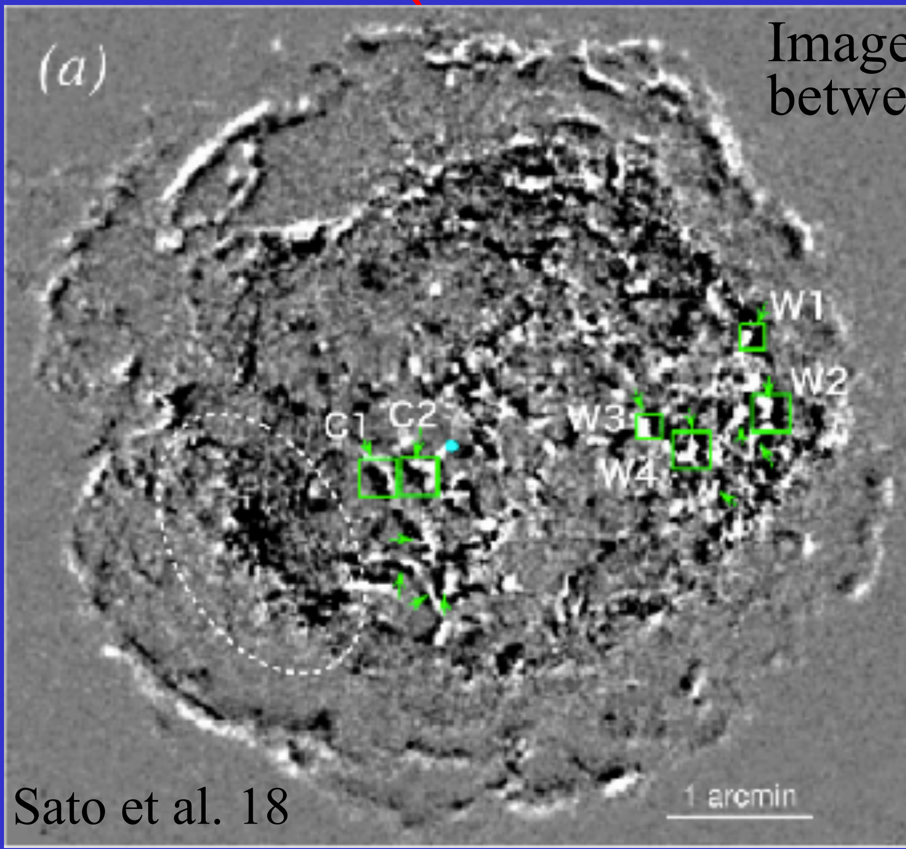
Evidence of
fast particle acceleration
and of B ~ mG
(strong amplification)

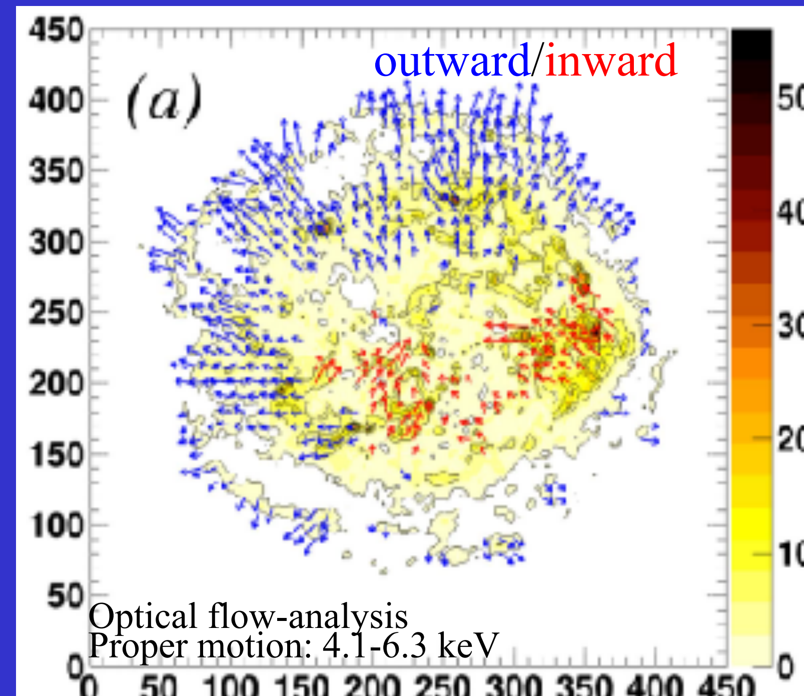


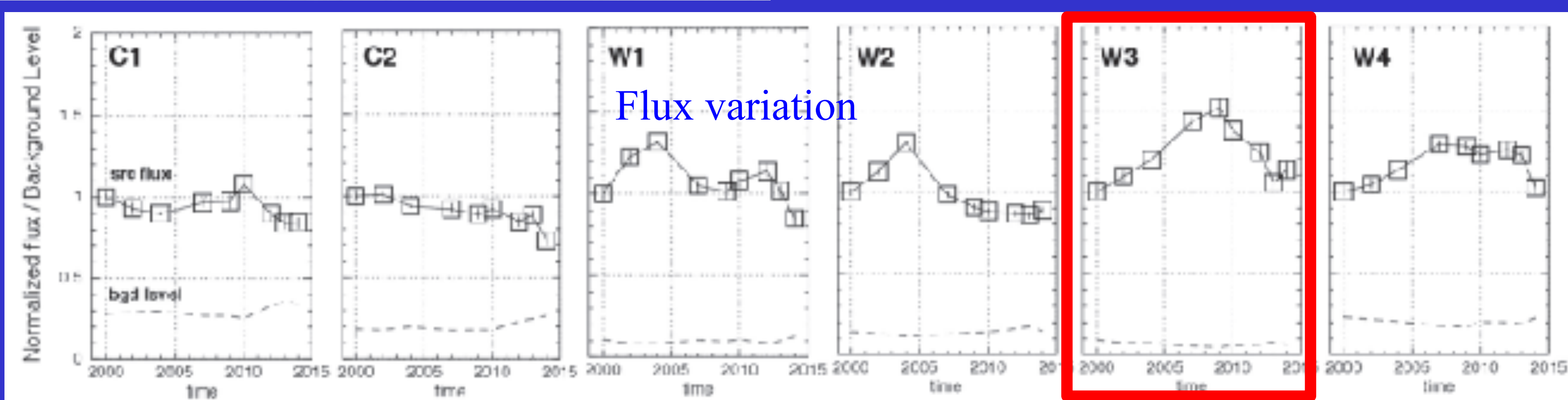
Uchiyama et al. 07

Cas A (Central/West): Inward shocks

Image difference (4.2-6 keV)
between 2000 and 2014 (Chandra)

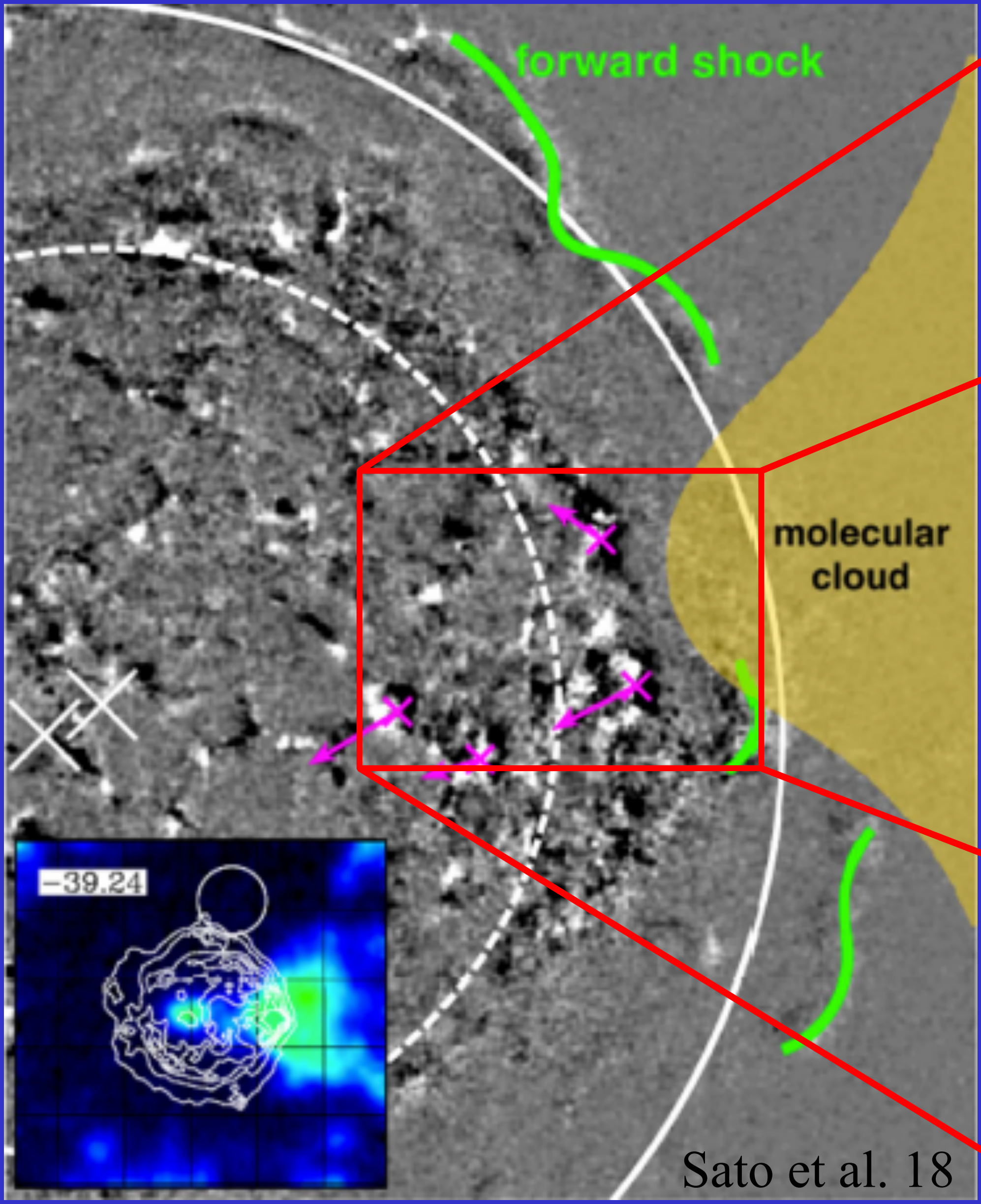




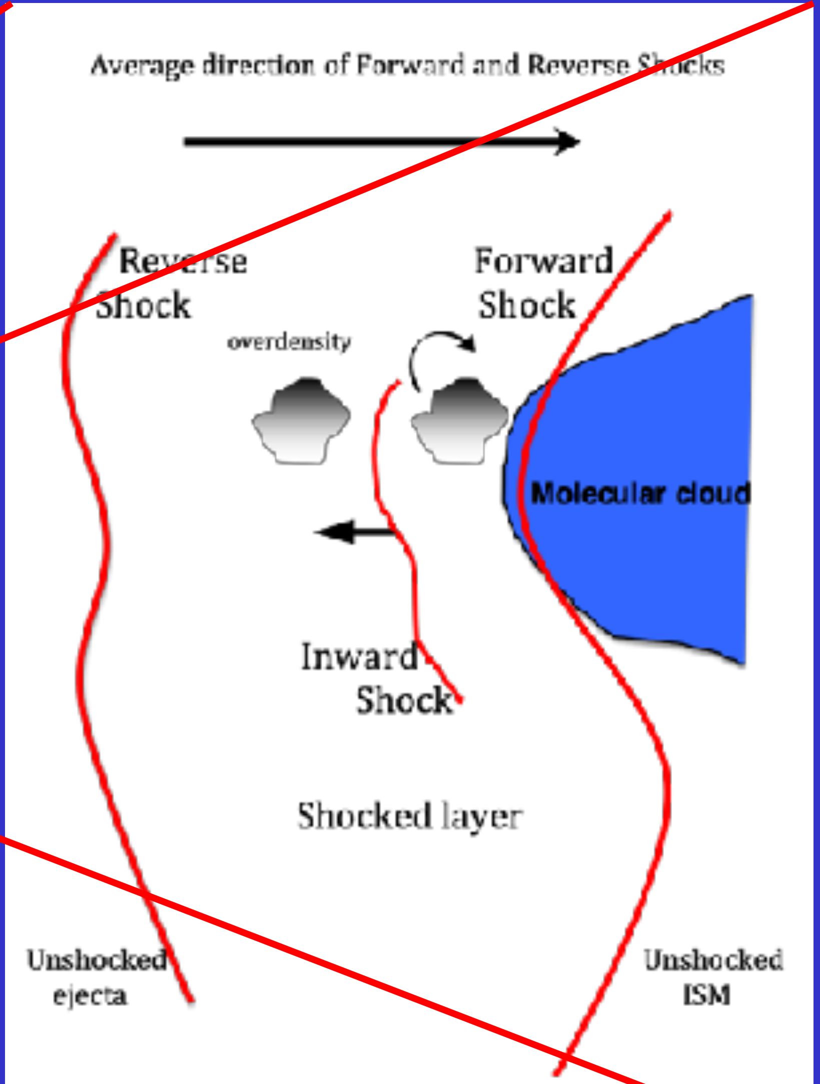


Inward shock/turbulent medium

Can flux increase be generated by magnetic enhancement only?



Sato et al. 18



FF et al 18

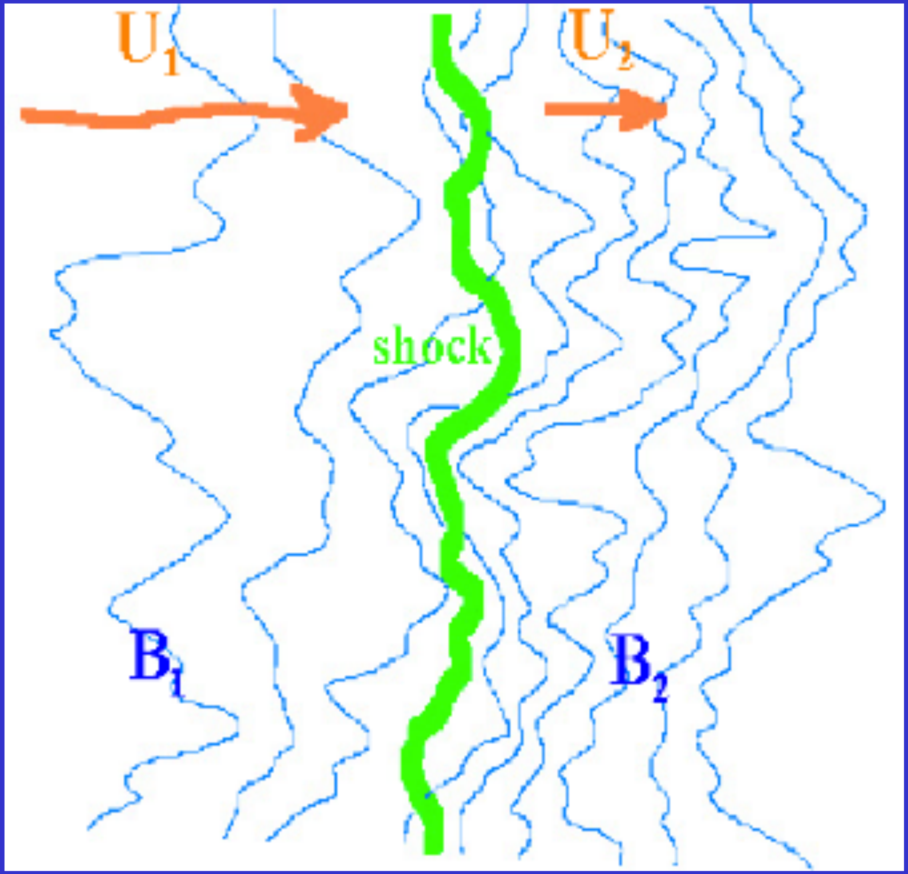
Jump conditions

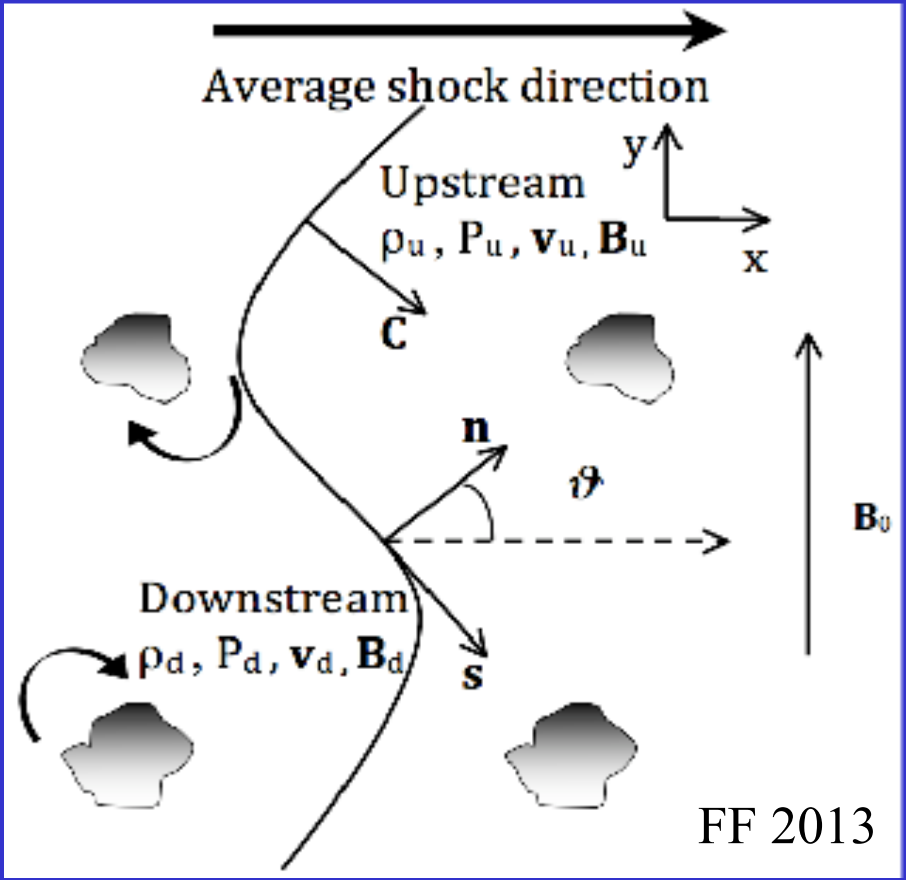
Ordinary Rankine-Hugoniot jump conditions cannot be applied to a rippled shock

Local orthonormal frame can be defined:

To first order in θ (large curvature radius)

Perpendicular field upstream





FF 2013

Vorticity downstream

Non-linear but can be computed analytically

$$\delta\omega_z = \frac{r-1}{r}\left[\left(\frac{C_r}{\rho}\right)_u \partial_s \rho + \partial_s C_r\right] - \frac{B_n \delta B_s}{4\pi\rho C_r}\partial_s \vartheta$$

FF 2013

r: compression, C_r: shock speed

Baroclinic term

$$\frac{\partial \omega}{\partial t} = \nabla \times (\mathbf{v} \times \omega) + \frac{\nabla\rho \times \nabla P}{\rho^2}$$

Energy deposited in vortical motion grows with shock speed
Shear or power spectrum

Finite curvature radius (zero for planar shock)

Turbulent field backreaction
Strongly rippled -> higher amplified field
Large B_0 makes resistance to filed lines tangling

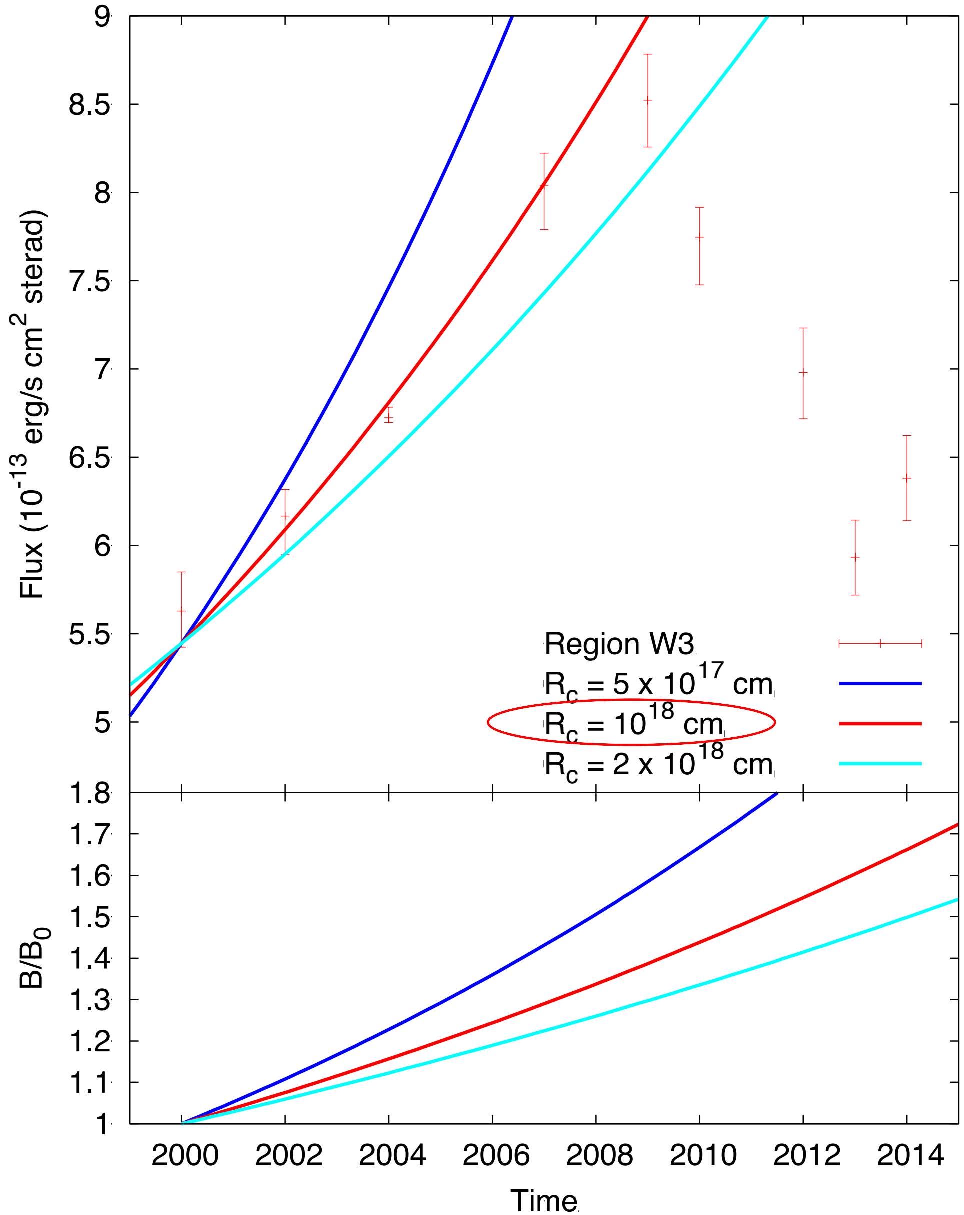
growth rate

backreaction

$$\frac{\varepsilon}{\varepsilon_0}(t) = \left(\frac{B}{B_0}\right)^2 (t) = \frac{e^{2t/\tau}}{1-\alpha\tau(1-e^{2t/\tau})v_A^2/2}$$

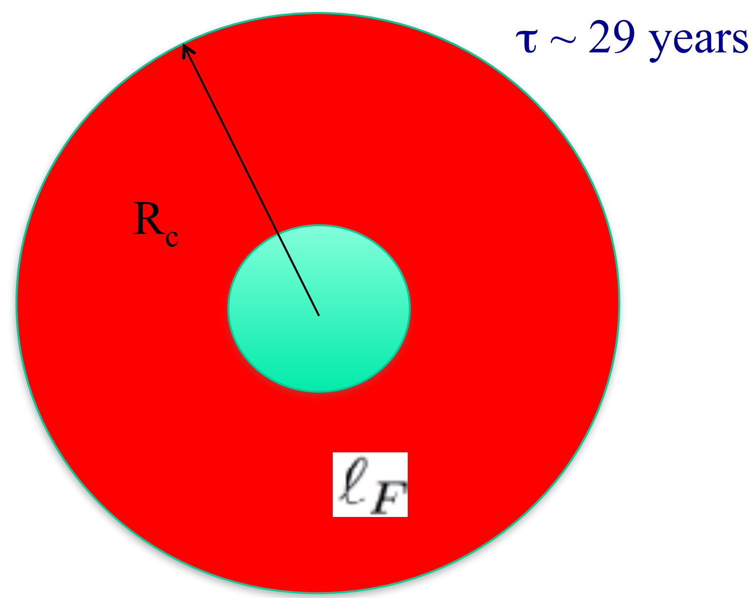
$$\tau \sim \frac{r}{r-1}\frac{1}{C_r}\frac{R_c \ell_F}{R_c + \ell_F} \sim \frac{\ell_F}{C_r}$$

Flux increase



Synchrotron flux with B = B(t)

Shock speed, compression (i.e., spectral index), photon energy determined by observations; only two free parameters: Rc and ℓ_F



Flux increase might be related to a slow particle acceleration, instead of B-growth, or to a B-growth due to a different mechanism

Conclusion

Shocks in nature cross inherently turbulent media.
This affects the diffusion of charged particles at shocks

Multi-epoch monitoring (Chandra) of shock/molecular cloud interactions provides us with invaluable information of the dynamics at shocks and can be quantitatively related to enhancement of magnetic energy

The turbulence scales as the Alfven Mach number (of order of a few unities). Consistent with not very strong turbulence generated here (diffusion coefficient different from Bohm limit).