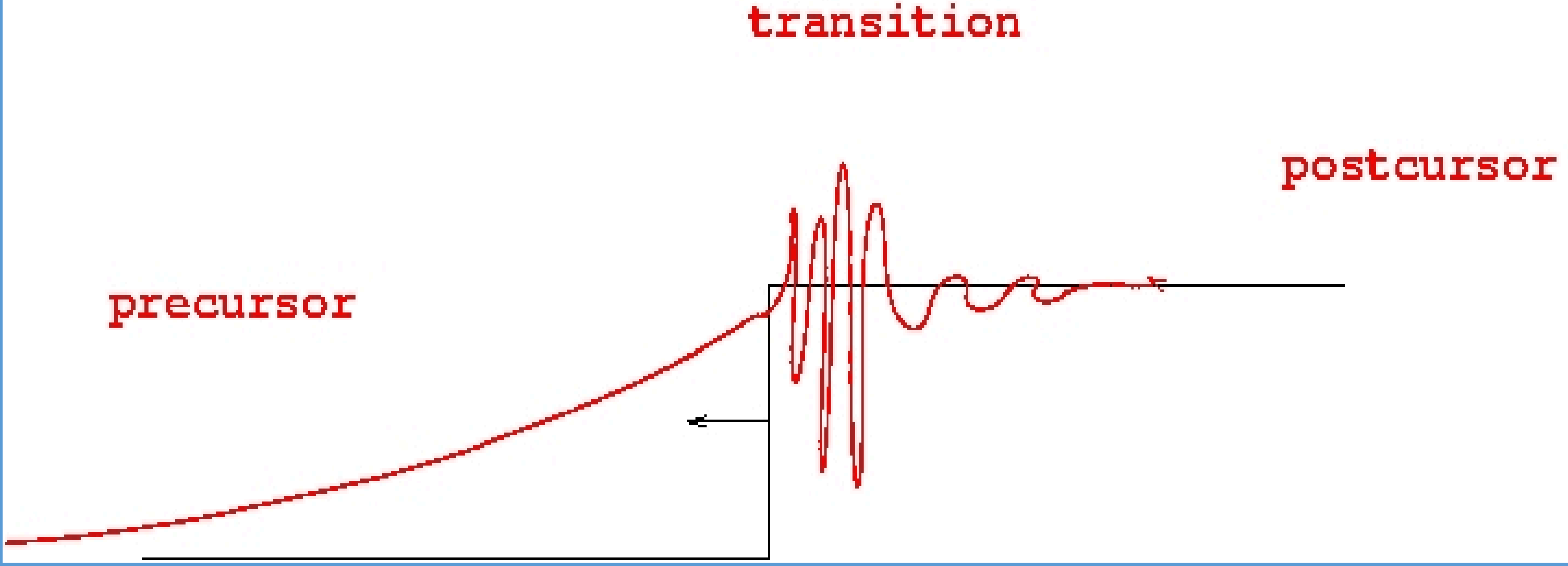
Cluster Diffuse Particle Acceleration and MHD

Plasma dynamics is to hydrodynamics as organic chemistry is to inorganic chemistry   ---Sterl Phinney

Walter Jaffe

Collisionless MHD shocks don't look like hydro shocks



- The transition region is where entropy is generated in plasma oscillations with characteristic size of

$\lambda_e = c/\omega_e$ ~10^6 cm. The whole region is ~1000 λ_e across.

Here, and in postshock chaos, CRs are reflected upstream

In the precursor, accelerated particles try to stream upstream, but generate Alfven waves which reflect them back downstream. The precursor can be (many) kpc across. Upstream+downstream reflections=acceleration

- MHD simulations show that turbulent dynamos build up in precursor and transition regions, so that downstream magnetic field >> upstream, certainly including turbulent fields and probably including large scale fields.
- Simulations are difficult because of huge range in scale sizes, but the conventional knowledge is that CR+B^2 energy flux downstream is comparable to kinetic energy flux upstream. This changes overal effect of shock.

- Normally shock transitions are described by the **Rankine–Hugoniot** jump conditions that encode conservation of mass energy and momentum. For HD these yield:

$r \equiv \rho_2/\rho_1 = (\gamma+1)/(\gamma-1+2/M^2)$; $kT_2/m = v_1^2*(r*(1+1/M^2)/ \gamma -1)/r^2$

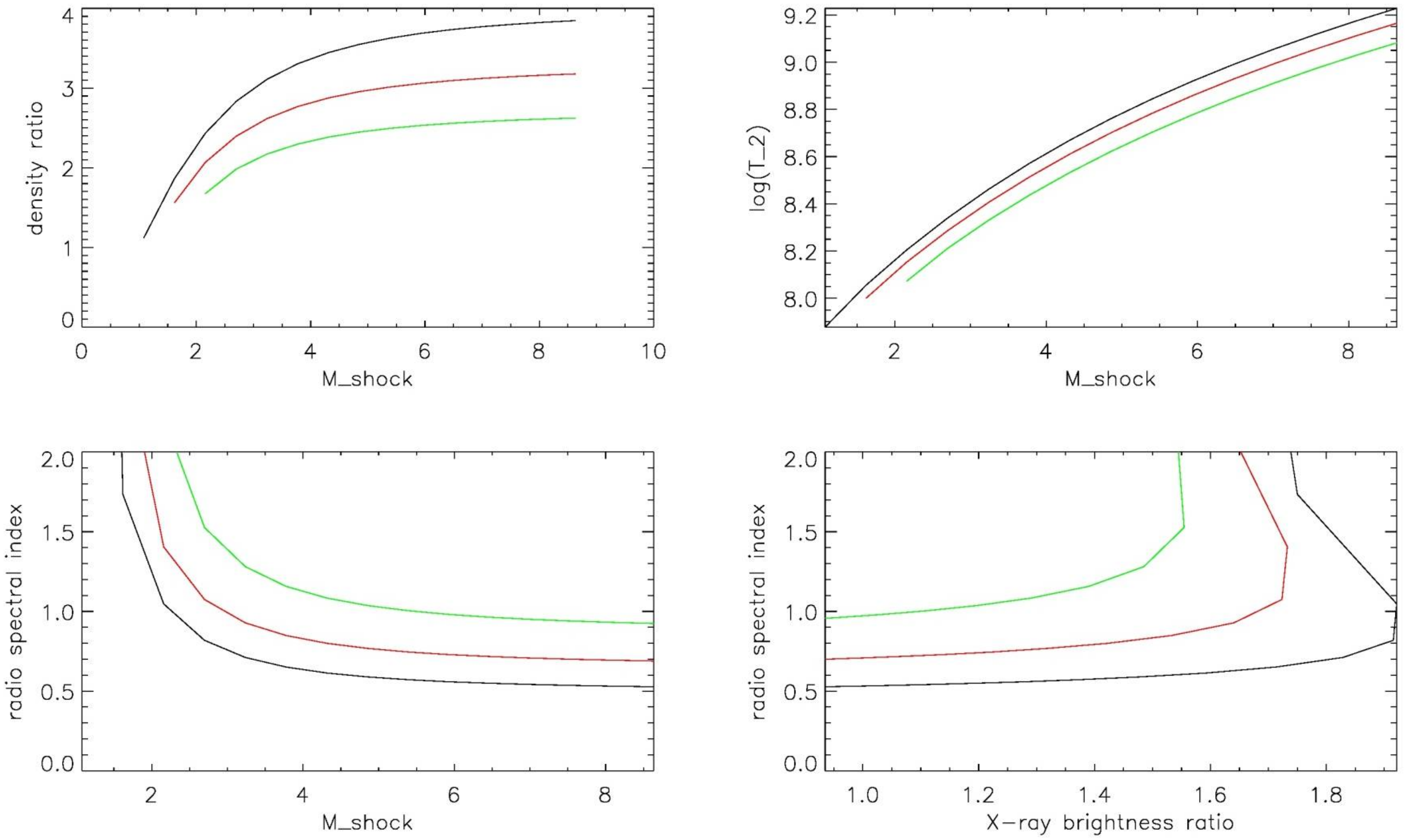
and Blandford,Bell, Axford et al. give the particle spectral index as **$g = 3r/(r-1)$** and the radio spectral index is

$\alpha = (g-1)/2$

If you allow creation of magnetic and CR energy, you get different results because there is additional output pressure and energy flux.

The following are diagnostic plots for different, constant, values of the ratio of output relativistic energy flux to input kinetic energy flux = [0., 0.1, 0.2]

For different assumptions you get different, even inverted, curves, c.f. **A.M. Bykov et al., 2008 Sp. Sci. Rev 134, 119**


density ratio
M_shock
log(T_2)
M_shock
radio spectral index
M_shock
radio spectral index
X-ray brightness ratio

- Other interesting effects:
- Heating of ions occurs mostly at transition region, downstream from CR acceleration; electron heating occurs downstream from ions, so displaced from initial radio emission
- Any E or B field fluctuations are also scattered by CRs, just like photons in Compton emission. Transition region is relatively thin, but has lots of short wavelength electric fields, with energy density ~B^2 and scalelength 10^{-4} of synchrotron scale.

MHD Nuggets for analyzing radio shock fronts:

- X-ray, α relations may be different than you expect
- Radio and X-ray transitions may be spread out by precursor
- Radio transition may preceed X-ray transition, and may be turbulent (i.e. unpolarized)
- Compton scattered plasma waves may give a low surface brightness infrared echo of radio spectrum, shifted 10^4 in frequency
- Why do we usually see them on the edges of clusters?

Things to do

- Better simulations
- Check X-ray/radio alignment
- Look for polarization
- Lower surface brightness maps to see face on shocks
- Infrared maps? $L_{IR} / L_{radio} \sim 10^{-6}$, mostly due to thinness of transition zone, probably not feasible

- What about in situ turbulent acceleration?
- Jaffe(1977) found that too much turbulent input energy was required, but in the meantime, large-scale structure assembly shows that largest input of energy is infalling subclusters.
- Schickeiser et al (1987, A&A 182,21) was more favorable but uses short CR scattering length.
- Chief problem is extrapolating turbulence from input scale (10^{+4} pc) to CR-resonance scale (10^{-4} pc)

If cluster is assembled by infall over 10^{10} y, then average power input is >~10^{47} erg/s, of which ~10% in baryons (mostly gas). Some of the baryon energy is dissipated thermally in shocks but a fair fraction will be initially turbulent kinetic energy (+ a fraction of the dark matter kinetic energy).

Assume 10% of gas energy injected every 10^9 y on 300 kpc scale and Kolmogorov decay ($v \sim l^{1/3}$) until $v \sim V_a$ (100 km/s). This happens at l_A ~10 kpc for B~1 μG , then B field stops turbulence and you get Alfven cascade (agrees with radio Rotation Measures).

- At shorter lengths we get an Alfven cascade with $(dB/B)^2 \sim (dv/V_A)^2 \sim (l/l_A)^{-\beta}$ with different theories giving
- $\beta \sim 2/3 \to 1$.
- The big problem is that the acceleration of electrons occurs when $l \sim r_{synch} \sim 10^{14}$ cm, which is 8 orders of magnitude $< l_A$. So the exact value of β makes a big difference.
- 2nd order Fermi acceleration balanced with synchrotron losses produces a (slow) exponential spectrum up to a Lorentz factor $\gamma_s \sim (m_e/m_H)/(n_e\, l_A\, \sigma_{thomp}) * (l_A/r_{synch})^{1-\beta} \sim 10 * 10^{[1\to 4]}$

- The radio emission requires electrons with $\gamma \sim 10^{3\text{->}4}$ so this requires $\beta \sim 2/3$ or alternatively that l_A is 100 times smaller than estimated (i.e. 100 pc). $l_A \sim L_{injection} (V_A / V_{injection})^3$ so this can be achieved by reducing $L_{injection}$ a lot or by reducing V_A by a little (factor of 10), most easily by reducing B.
- Fooling around with β changes the form of the spectrum a little.

- MHD Nuggets for analyzing radio halos:
- Halo characteristics will correlate with galaxy kinematics
- Because they are result of chaotic processes, they will vary strongly from cluster to cluster; there may be no *standard* radio halo.
- Large scale end of velocity turbulence limited by radio tails if co-spatial
- Detailed, high-density rotation measure data limits large-scale end of B-spectrum

Things to do

- Better simulations to check values of β
- Dark matter+baryon cluster simulations to establish input turbulent spectrum
- Galaxy redshifts+classification model to quantify turbulent injection energy per cluster
- Lots of halos + classification model to quantify variability in radio spectra and morphology.
- Lots of radio tails to estimate turbulent velocities.