Acceleration of Thermal and Non-thermal Seed Populations at Oblique Coronal Shocks

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Solar Energetic Particles

Sources

- Accelerated by a variety of solar processes
- Seed particles from the ambient solar wind
- Transport affected by interplanetary magnetic field
- Mostly protons, but also heavier ions

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Observations

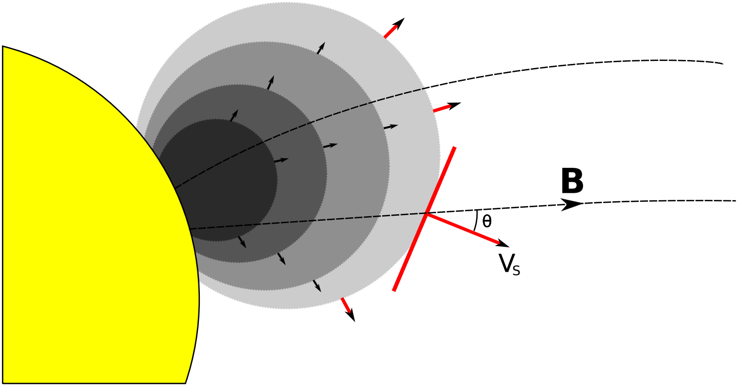
- A major player in space weather
- Energies up to hundreds of MeVs
- Particles detected in-situ

Acceleration at coronal shocks

1st order Fermi-acceleration

- Plasma shock travels through corona
- Ambient particles encounter shock, receive energy
- Particles travel along magnetic field lines
- Turbulence in front of shock scatters partices back towards the shock
- repeated shock encounters lead to high energies

The geometry

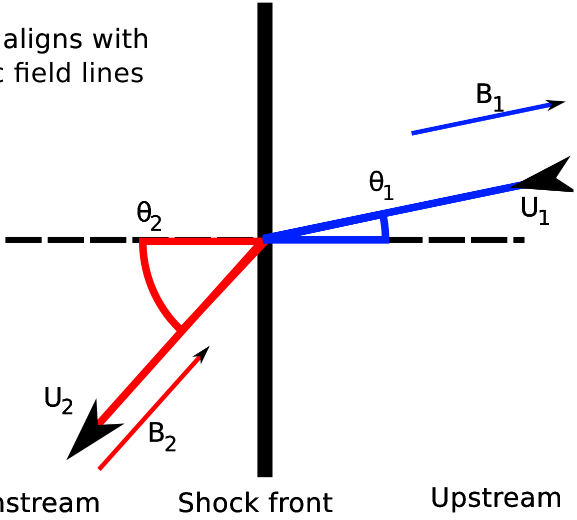


Shock fronts

Dynamics

- Strong shock velocities: 1000 . . . 2000 km/s
- Spherical shocks can encounter field lines at varying angles
- Calculate plasma and magnetic compression ratios
- Align plasma flow with magnetic field lines

The de Hoffmann – Teller frame



Gas flow aligns with magnetic field lines

Rankine-Hugoniot equations

Solving shock compression ratios

Alfvénic Mach number $M = u_1/v_\mathrm{A}$ is known. Parametric solver of z finds gas compression ratio r_k.

$$M^2 = (1+z) r_\mathrm{k}(z)$$

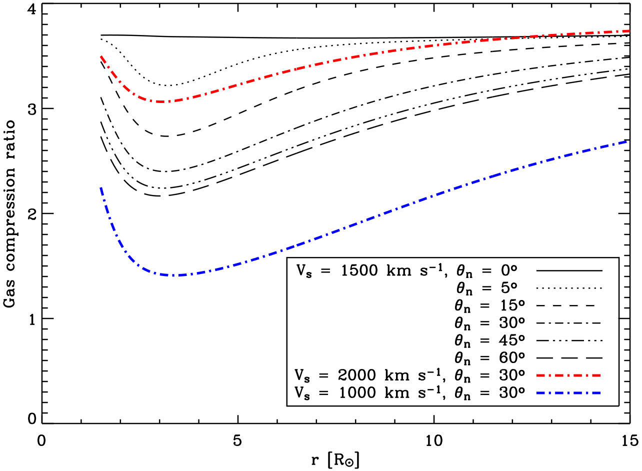
$$r_\mathrm{k}(z) = \frac{(z+1)\left(z^2(\gamma+1)\cos^2\theta_\mathrm{n} + (1-\gamma z)\sin^2\theta_\mathrm{n}\right) - z^2\gamma\beta}{(z+1)(z^2\left(\gamma-1\right)\cos^2\theta_\mathrm{n} + (1+(2-\gamma)z)\sin^2\theta_\mathrm{n})} \tag{1}$$

Magnetic compression ratio r_b solved with r_k.

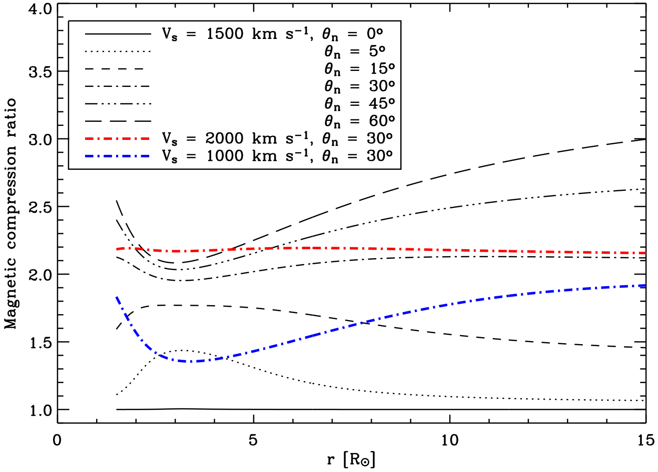
$$r_\mathrm{b} = \sqrt{\cos^2\theta_\mathrm{n} + (1-\cos^2\theta_\mathrm{n})\left(\frac{u_1^2 - v_\mathrm{A}^2}{u_1^2 - r_\mathrm{k} v_\mathrm{A}^2} r_\mathrm{k}\right)^2} \tag{2}$$

Downstream flow velocity given as $u_2 = \frac{r_\mathrm{b}}{r_\mathrm{k}} u_1$

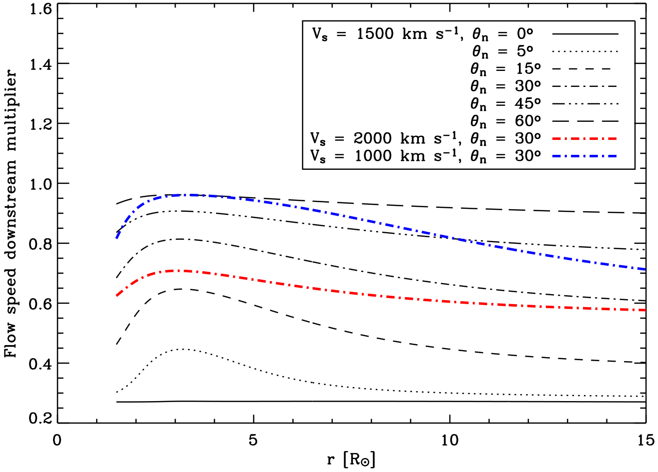
Gas compression ratios



Magnetic compression ratios



Flow speed multipliers

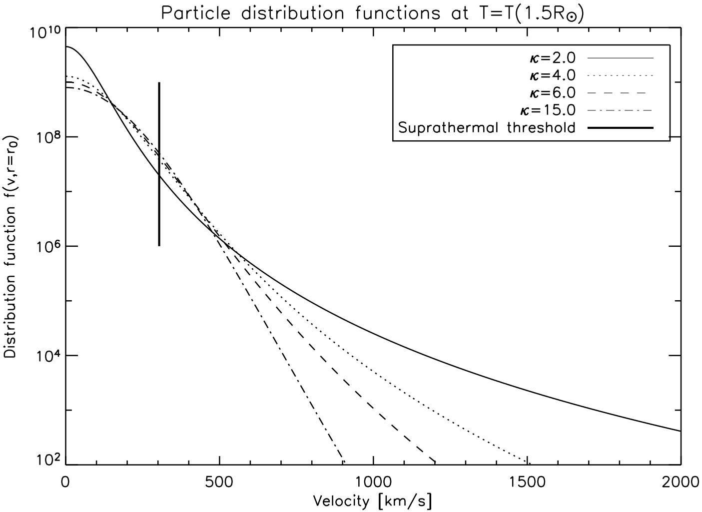


Particles encountered by the shock

Suprathermal and thermal populations

- Thermal background solar wind
- Suprathermal remnant populations
- Can be modeled as isotropic or pancake pitch-angle distributions
- Temperature profile + κ-distribution

κ-distributions

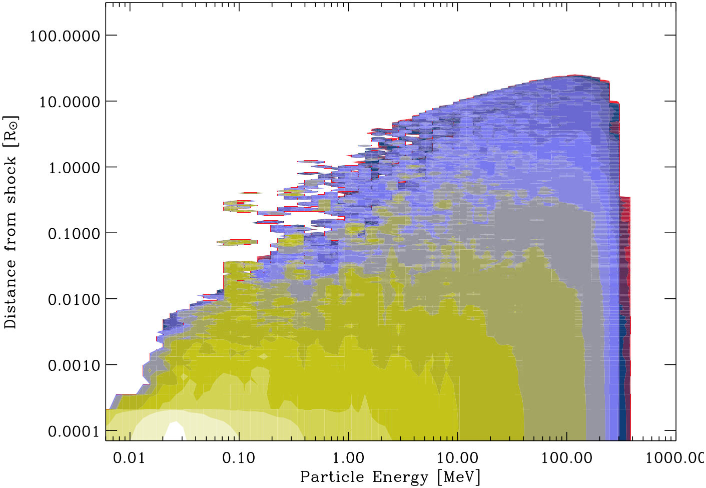


Shock encounter

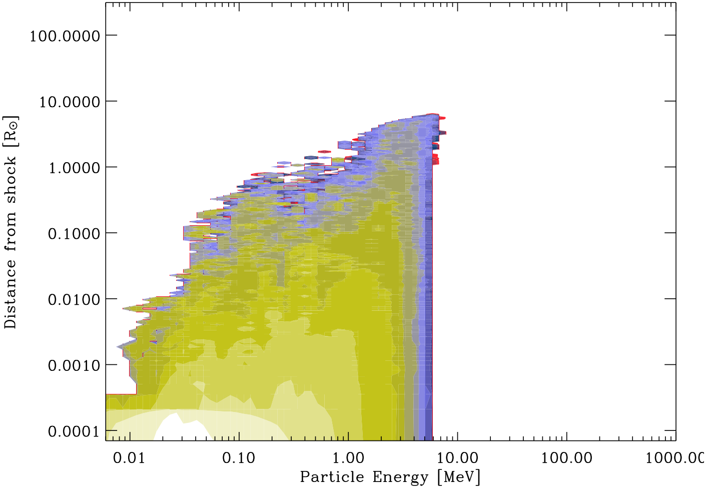
Particle distribution transformation

- Analyze how population encounters shock
- Cross-shock potential and magnetic mirroring
- Heavy turbulence in downstream scatters particles
- Particles may re-enter upstream

$V_s = 1500 \text{ km s}^{-1}$, $\theta_n = 0°$



$V_s = 1500\ \mathrm{km\ s^{-1}}$, $\theta_n = 5^\circ$



Simulation results

Maximum energy

- $\theta_{\rm n} = 0°$: 300 MeV
- $\theta_{\rm n} = 5°$: 6 MeV
- 4-fold difference in particles surviving initial shock encounter
- What can possibly explain this?

Analytical approach

Particles which cannot re-enter the upstream?

- Attempt to solve speed thresholds for mirroring
- Calculate downstream speed v_2 for transmitted particle
- Return impossible if $v_2 < u_2$
- Find maxima for given particle pitch-angles and speeds

Analytical approach

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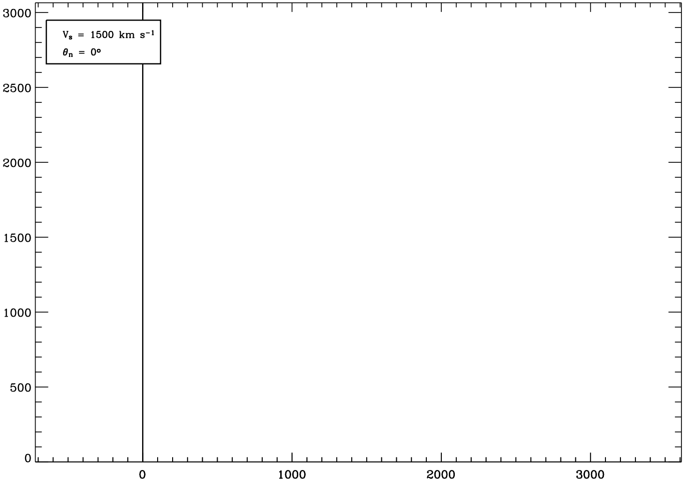
…let's not go there.

Graphing populations



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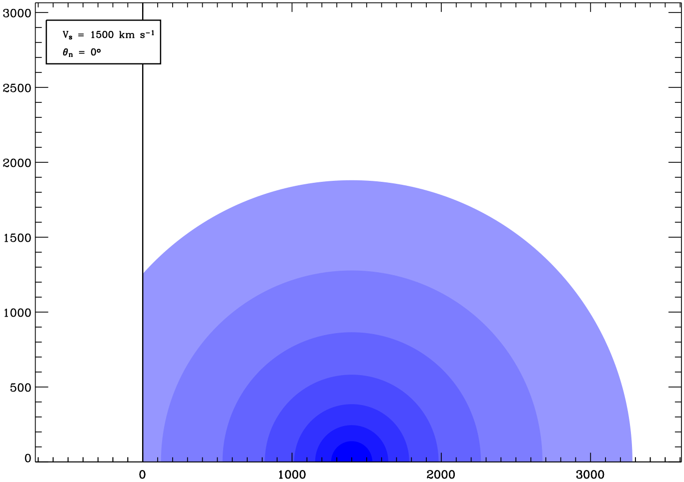

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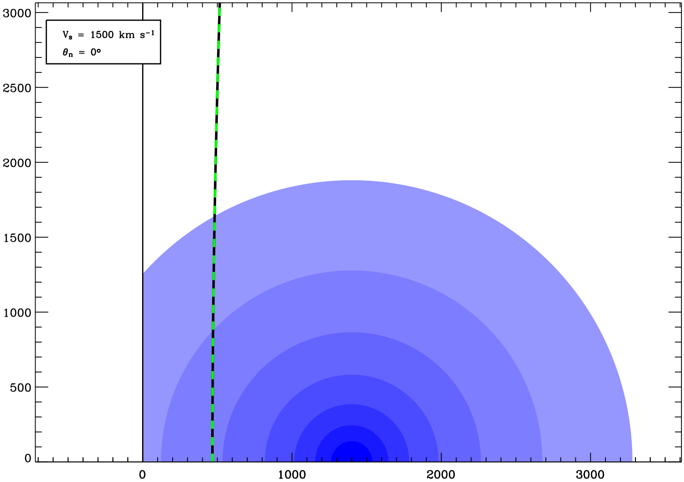

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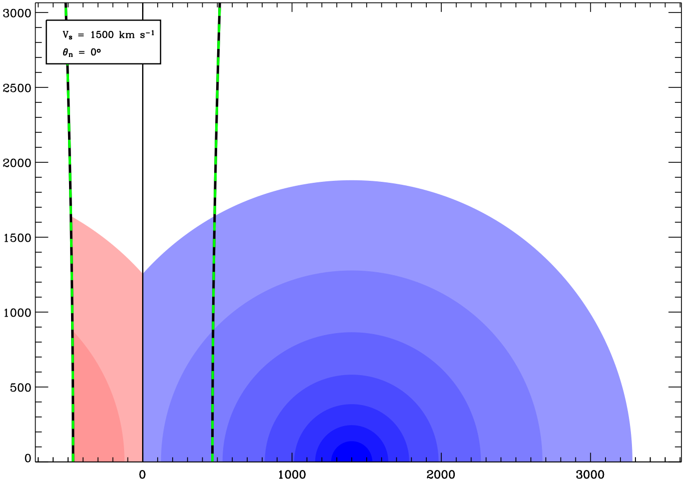

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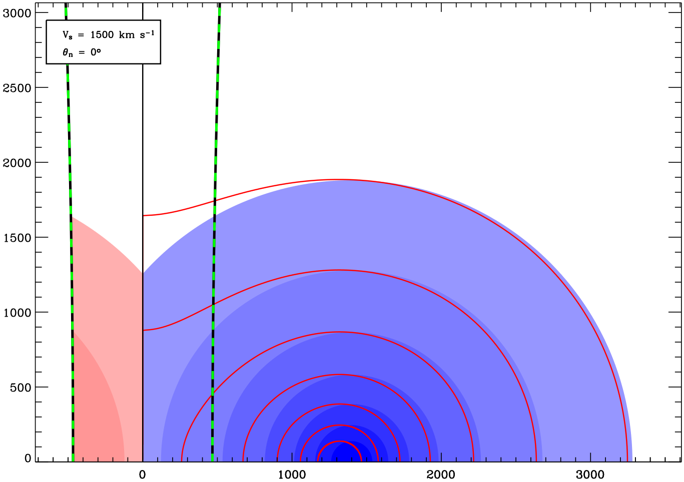

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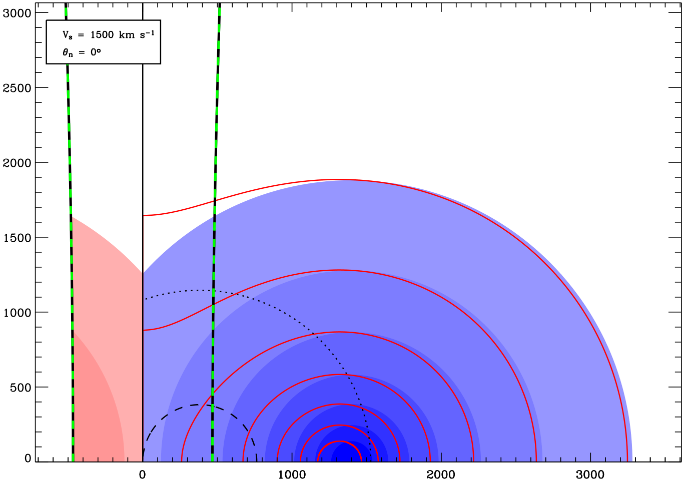
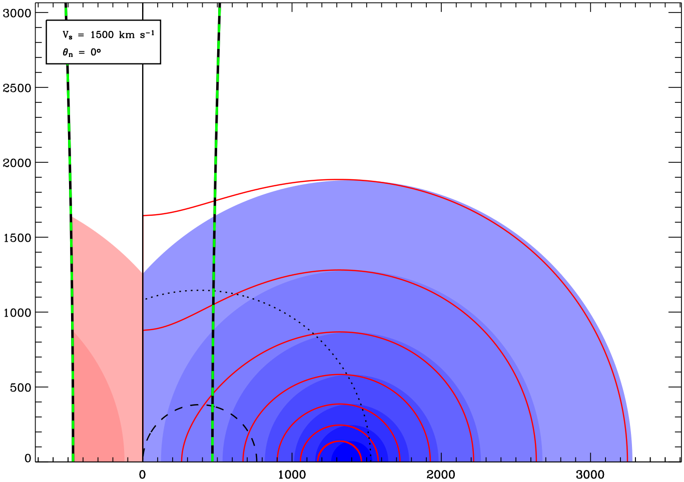


Effect of shock obliquity: suprathermal



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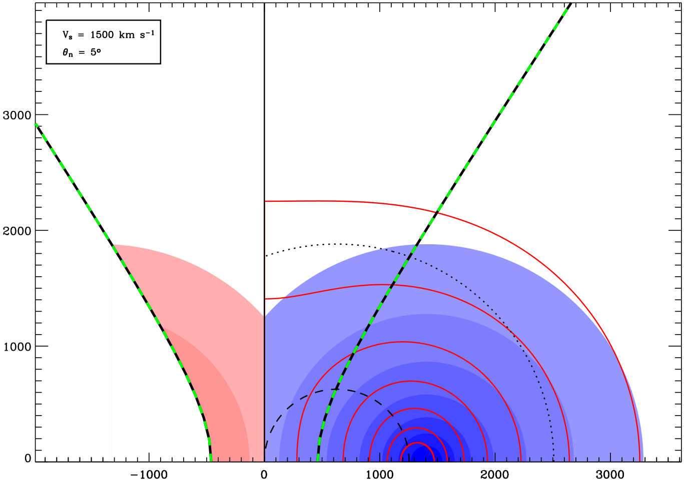

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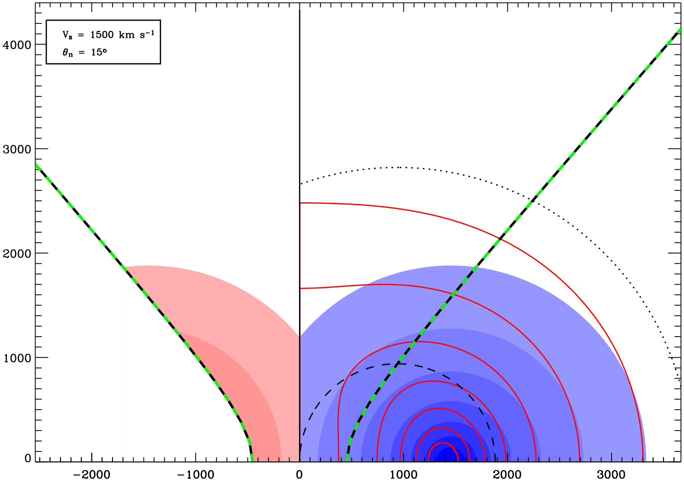

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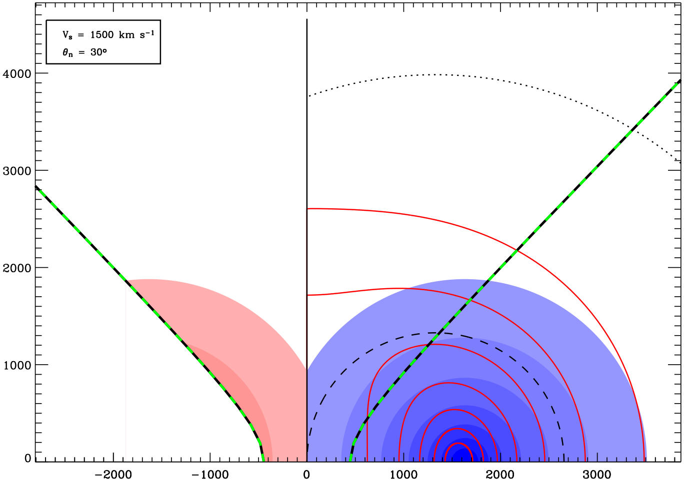
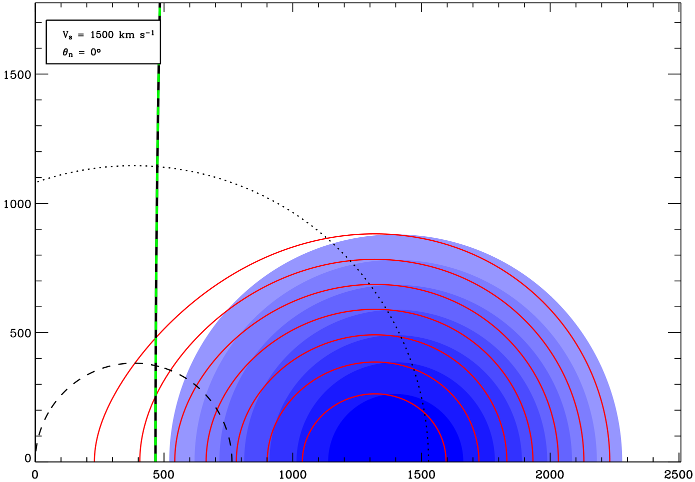


Effect of shock obliquity: thermal



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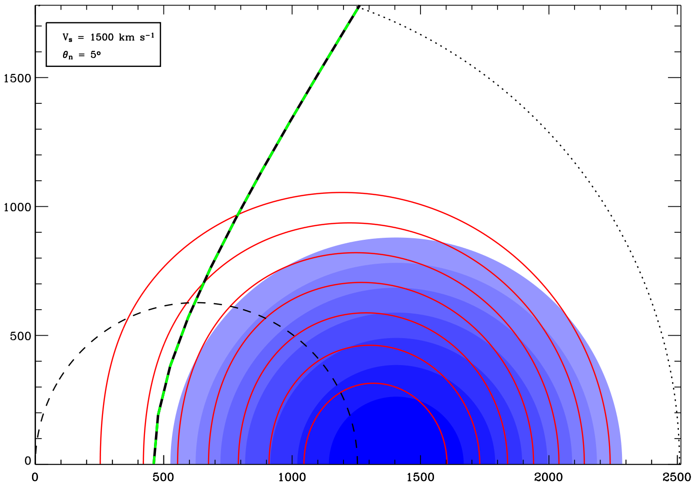

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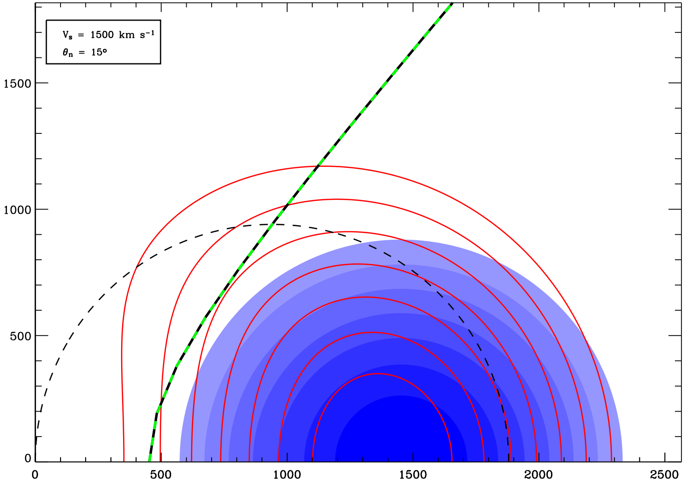

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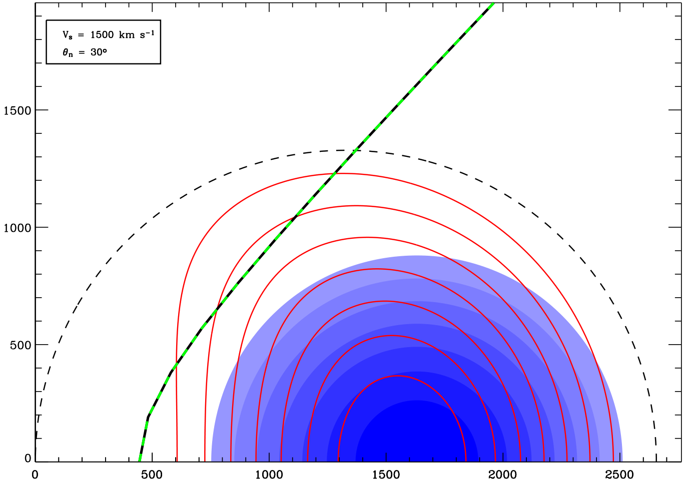

What does this tell us?

Small angle θ_n can have large effect

- Relatively low shock-normal angles result in high flow factors
- Cold population approaches the "no-fly zone"
- Total number of particles falls
- Bootstrapped acceleration process stalls

Conclusions

Simulation results vindicated?

- Reason behind intense θ_{n}-dependence found
- Do completely parallel shocks exist?
- What is the significance of the shock thickness?
- Wave populations in downstream & cross-helicity?

End

Thank you!