

HH211 Credit: ESA/Webb, NASA,
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Kinetic study of shock formation in protostellar jets

Jakub Gazdoš

Anabella Araudo, Jan Benáček, Michelle Tsirou

Young Stellar Object (YSO), about 1 million years old, $M \approx 1 M_{\odot}$
Interaction of rotating accretion disk launches jets from the magnetic poles.

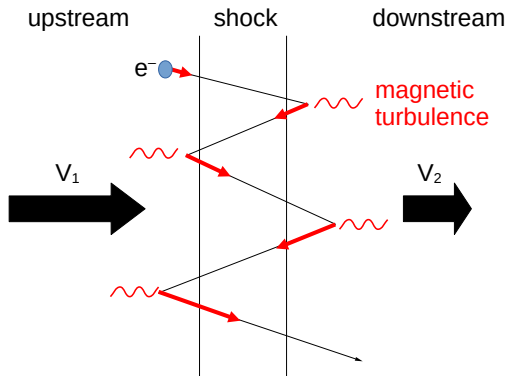
Jets (300–1500 km/s) impact surrounding medium producing termination shocks.

Observations with Giant Metrewave Radio Telescope (GMRT)
Ainsworth et al. (2014) report fit of spectral index $\alpha = -0.89$
indicative of synchrotron radiation produced by a population of relativistic electrons.

What is the acceleration mechanism?

Fermi acceleration

produces non-thermal high energy particles



finite shock width $\approx$ mean free-path of thermal protons/ions

$\gg$ mean free-path of thermal electrons

$\Rightarrow$ thermal electrons cannot cross shock, acceleration impossible

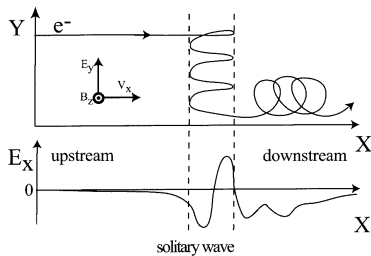
Injection problem

Thermal electrons need pre-acceleration to enter Fermi regime

1. Shock Surfing Acceleration (SSA)

Hoshino and Shimada (2002)

Electrons trapped and accelerated in strong localised electrostatic waves (ESW)



2. Stochastic Shock Drift Acceleration (SSDA)

Katou and Amano (2019)

1D simulation using ACRONYM PIC code

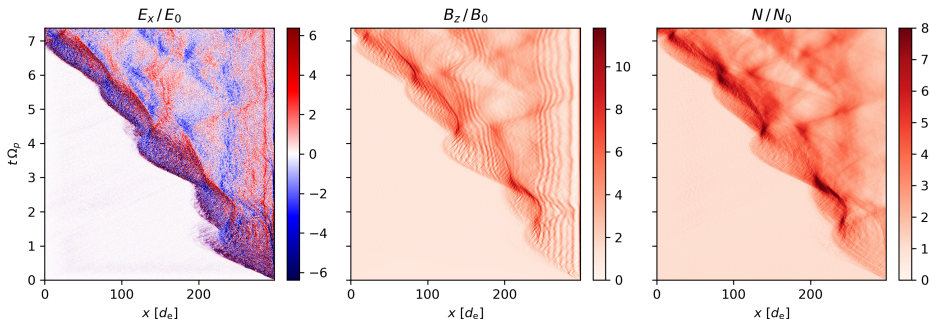
following Hoshino and Shimada (2002)

low-temperature ($v_{th} = 0.0037 c$) electron-proton plasma beam
with bulk velocity $v_x = v_0 = 0.25 c$

perpendicular background magnetic field $B_z = B_0$

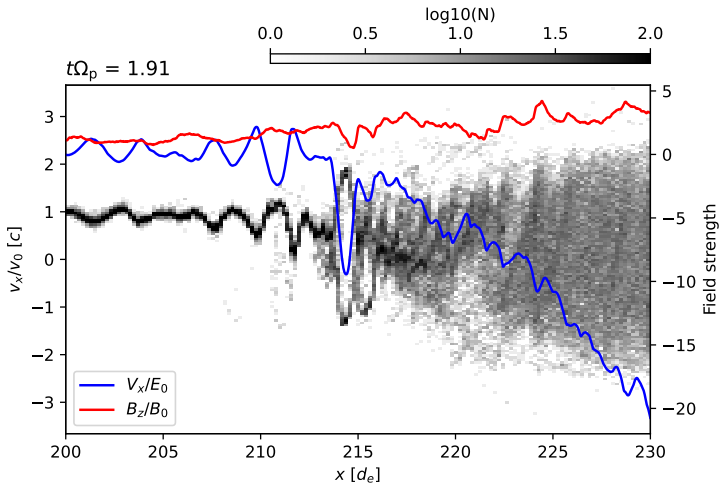
corresponding motional electric field $E_y = E_0 = v_0 B_0$

particles are reflected at right boundary



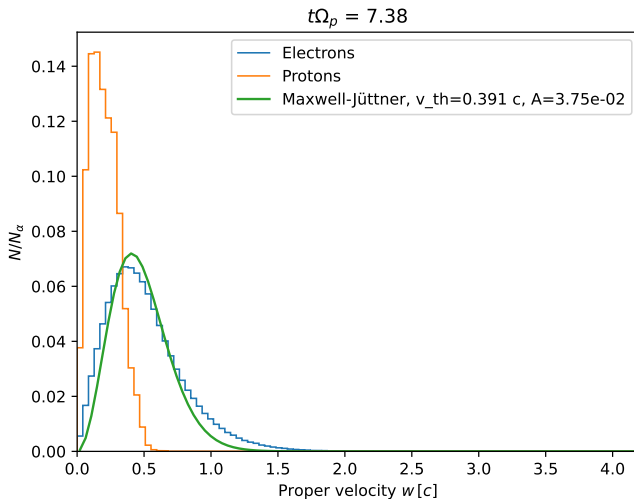
Phase space

Snapshot at $1.9 t \Omega_p$ zoomed in around the shock region.
An electron hole at around $215 d_e$ associated with ESW in the electric field and a dip in amplitude of the magnetic field.



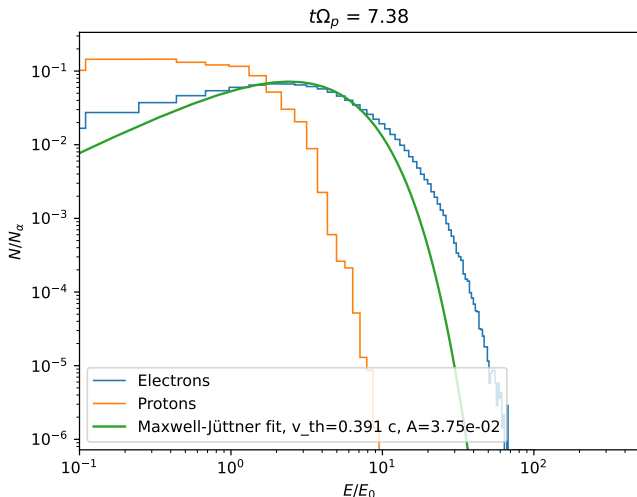
Particle velocity spectra

fitted by Maxwell-Jüttner.



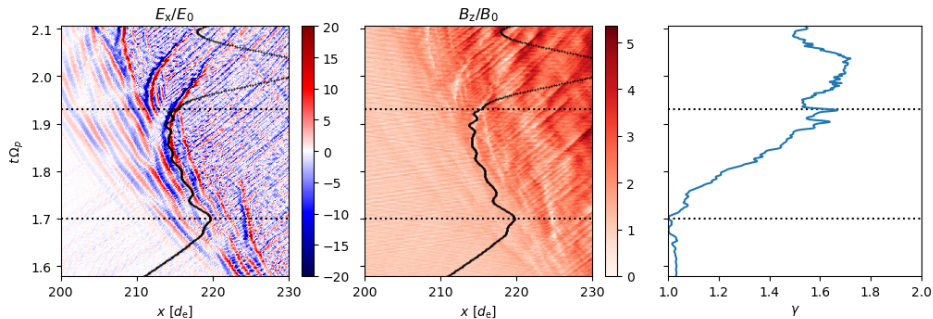
Particle energy spectra

fitted by Maxwell-Jüttner distribution reveals non-thermal population.



Particle trajectories

shows acceleration in the region of the ESW



1D shock in protostellar jet environment

physical parameters from Araudo, Padovani, and Marcowith (2021)

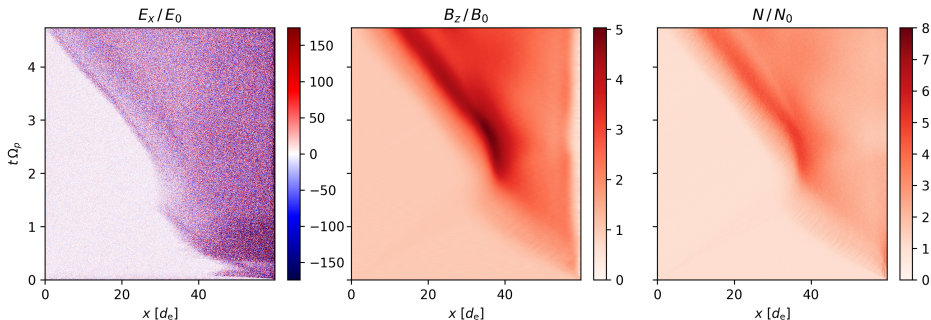
$$v_0 = 1000 \text{ km/s} = 0.003 c$$

$$B_z = 1 \text{ mG}, M_A = 7.2$$

$$T = 10^4 \text{ K} \rightarrow v_{\text{th}} = 0.0013 c$$

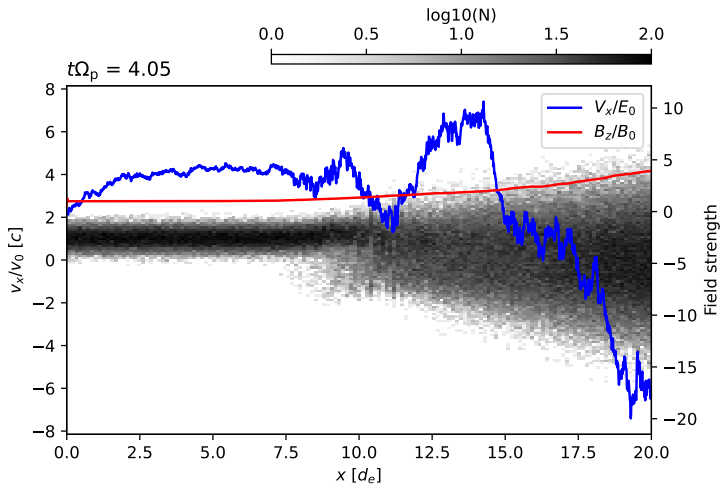
$$\text{plasma } \beta = 0.35$$

$$m_p/m_e = 20$$



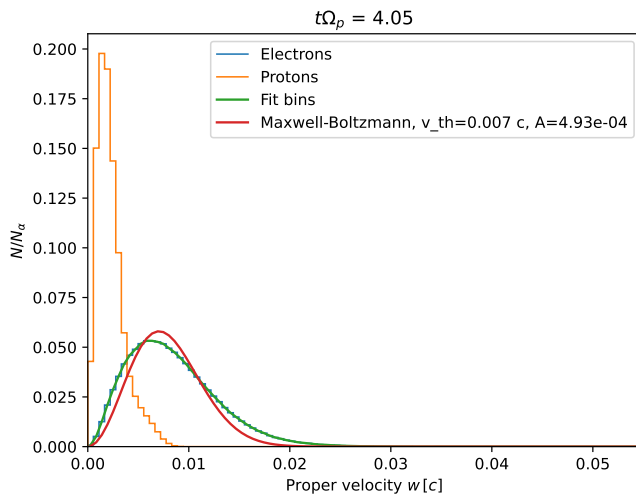
Preliminary results

Phase space, electric potential V_x , magnetic field B_z



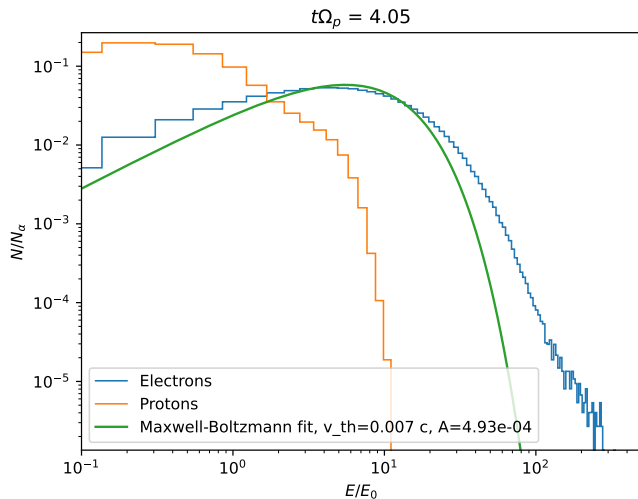
Preliminary results

Particle velocity spectra



Preliminary results

Particle energy spectra



Summary

Reproduced results of Hoshino and Shimada (2002) showing

- ▶ the formation of strong ESWs accompanied by holes in the electron phase-space
- ▶ non-thermal population of electrons accelerated by the shock
- ▶ particle trajectories indicating acceleration by the ESW

Preliminary 1D simulations of protostellar jet environment
weaker shock, high thermal noise

Bibliography



Ainsworth, Rachael E. et al. (Sept. 2014). "Tentative Evidence for Relativistic Electrons Generated by the Jet of the Young Sun-like Star DG Tau". In: *ApJ* 792.1, L18, p. L18. DOI: [10.1088/2041-8205/792/1/L18](https://doi.org/10.1088/2041-8205/792/1/L18). arXiv: 1408.1892 [astro-ph.SR].



Araudo, Anabella T, Marco Padovani, and Alexandre Marcowith (June 2021). "Particle acceleration and magnetic field amplification in massive young stellar object jets". In: *Monthly Notices of the Royal Astronomical Society* 504.2, pp. 2405–2419. ISSN: 0035-8711. DOI: [10.1093/mnras/stab635](https://doi.org/10.1093/mnras/stab635). eprint: <https://academic.oup.com/mnras/article-pdf/504/2/2405/37680305/stab635.pdf>. URL: <https://doi.org/10.1093/mnras/stab635>.



Hoshino, M. and N. Shimada (June 2002). "Nonthermal Electrons at High Mach Number Shocks: Electron Shock Surfing Acceleration". In: *The Astrophysical Journal* 572.2, p. 880. DOI: [10.1086/340454](https://doi.org/10.1086/340454). URL: