Adiabatic-radiative shock systems in non-relativistic astrophysical jets

A key to enhance the gamma-ray emission

Anabella Araudo

(1) Laboratoire Universe et Particules de Montpellier - LUPM
(2) ELi Beamlines, Institute of Physics, Czech Academy of Sciences
(3) Astronomical Institute, Czech Academy of Sciences

In collaboration with Maria V. del Valle, A. Gintrand, A. Marcowith, Q.Moreno, M. Padovani, Francisco Suzuki-Vidal, V. Tikhonchuk, S. Weber

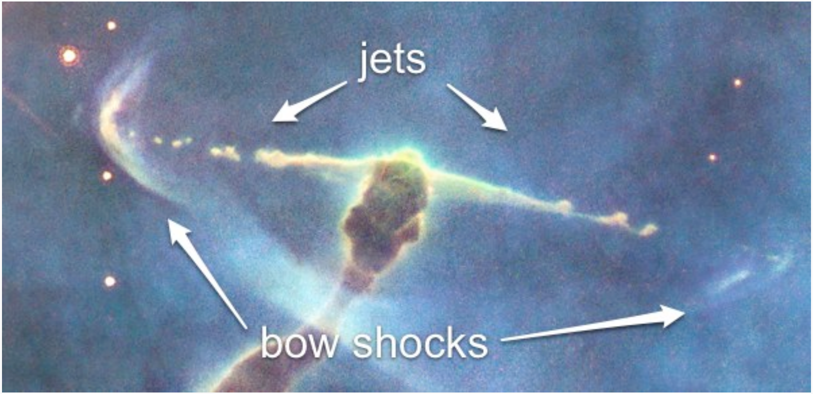
7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy
4-8 July, 2022 - Barcelona

Protostellar jets

Star forming regions

Protostellar jets

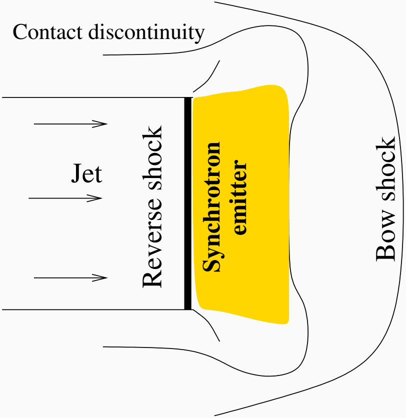
- Well known thermal emitters
- Increasing population of **non-thermal protostellar jets** (e.g. Purser et al. 2016)



Credit: NASA, ESA, M. Livio and the Hubble 20th Anniversary Team

Magnetic field amplification in YSO jets

- Electrons and protons are accelerated in the jet reverse shock
- Equipartition magnetic field: $B_{\rm eq}^2/8\pi = (1+a)U_e$
- Acceleration efficiency: $\eta_p = U_p/U_{\rm kin} \propto U_p/(n_{\rm j}v_{\rm j}^2)$



$$\frac{U_{\rm e}}{\rm erg\,cm^{-3}} \sim 5{\times}10^{-8}\left(\frac{d}{\rm kpc}\right)^2\left(\frac{S_\nu}{\rm mJy}\right)\left(\frac{R_{\rm j}}{10^{16}{\rm cm}}\right)^{-3}\left(\frac{\nu}{\rm GHz}\right)^{\frac{s-1}{2}}\left(\frac{B_{\rm s}}{\rm mG}\right)^{-\frac{s+1}{2}}$$

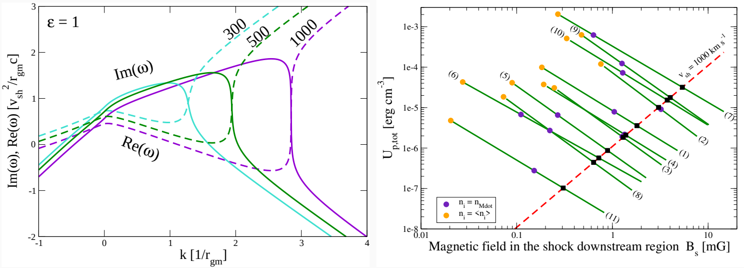
Bell instabilities in YSO jets

We consider a sample of 11 non-thermal radio jets (Purser et al. 2016)

Maximum growth rate:

$$\frac{\Gamma_{\rm max,NR}}{\rm s^{-1}} \sim 10^{-5}\left(\frac{\eta_p}{0.01}\right)\left(\frac{v_{\rm sh}}{1000\,{\rm km\,s^{-1}}}\right)^{3}\left(\frac{n_i}{10^3\,{\rm cm^{-3}}}\right)^{\frac{1}{2}}\left(\frac{E_{\rm p}}{\rm GeV}\right)^{-1}$$

$$\text{Saturation}: \quad \frac{B_{\rm sat,NR}}{\rm mG} \sim 0.3\left(\frac{U_{p,\rm tot}}{10^{-6}\,{\rm erg\,cm^{-3}}}\right)^{\frac{1}{2}}\left(\frac{v_{\rm sh}}{1000\,{\rm km\,s^{-1}}}\right)^{\frac{1}{2}}$$



Araudo et al. (2021)

Protons maximum energy - $E_{p,\mathrm{max}}$

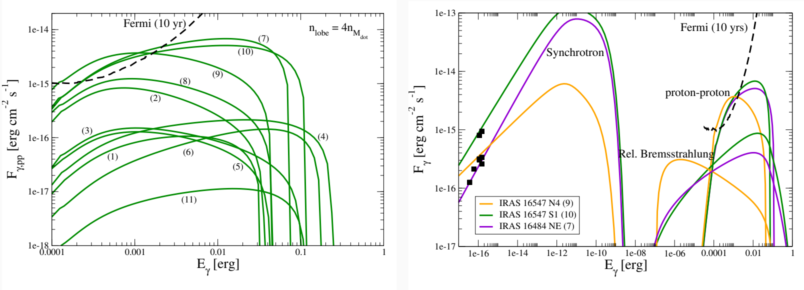
- $E_{p,\mathrm{max}}$ due to the **escape of particles upstream of the shock** $\Gamma_{\mathrm{max,NR}}(R_{\mathrm{j}}/v_{\mathrm{sh}}) > 5$ (Zirakashvili & Ptuskin 2008, Bell et al. 2013)
- For a distribution of protons $N_p \propto E_p^{-s}$

$$\frac{E_{p,\mathrm{max}}}{\mathrm{m_p c^2}} = \begin{cases} 70(2-s)\left(\frac{U_{p,\mathrm{tot}}}{10^{-5}\mathrm{erg\,cm^{-3}}}\right)\left(\frac{R_{\mathrm{j}}}{10^{16}\mathrm{cm}}\right)\left(\frac{n_i}{10^4\ \mathrm{cm^{-3}}}\right)^{-\frac{1}{2}} & s<2 \\ 70\log\left(\frac{E_{p,\mathrm{max}}}{\mathrm{GeV}}\right)^{-1}\left(\frac{U_{p,\mathrm{tot}}}{10^{-5}\mathrm{erg\,cm^{-3}}}\right)\left(\frac{R_{\mathrm{j}}}{10^{16}\mathrm{cm}}\right)\left(\frac{n_i}{10^4\ \mathrm{cm^{-3}}}\right)^{-\frac{1}{2}} & s=2 \\ \left[70(s-2)\frac{1}{m_p c^2}\left(\frac{U_{p,\mathrm{tot}}}{10^{-5}\mathrm{erg\,cm^{-3}}}\right)\left(\frac{R_{\mathrm{j}}}{10^{16}\mathrm{cm}}\right)\left(\frac{n_i}{10^4\ \mathrm{cm^{-3}}}\right)^{-\frac{1}{2}}\right]^{\frac{1}{s-1}} & s>2 \end{cases}$$

We find $E_{p,\mathrm{max}} \sim 0.1$ TeV for a sample of 11 non-thermal radio jets (Purser et al. 2016)

Gamma-ray emission

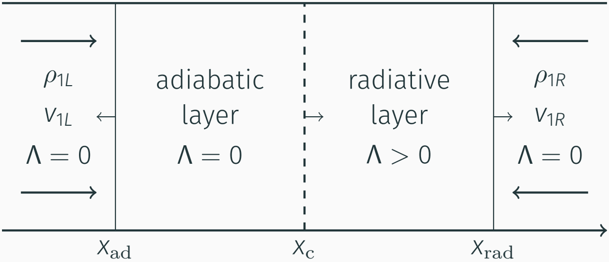
GeV-TeV protons (electrons) produce gamma-rays by proton-proton collisions (relativistic Bremsstrahlung) (Araudo et al. 2007, Bosch-Ramon et al. 2010)



Araudo, Padovani & Marcowith (2021)

Hybrid (adiabatic + radiative) leading working surface

New self similar solutions for the dynamics of the collision between radiative and adiabatic planar shocks (Gintrand, Moreno, Araudo, Tikhonchuk & Weber, 2021)



ρ_{1L}

v_{1L}

$\Lambda = 0$

adiabatic layer

$\Lambda = 0$

radiative layer

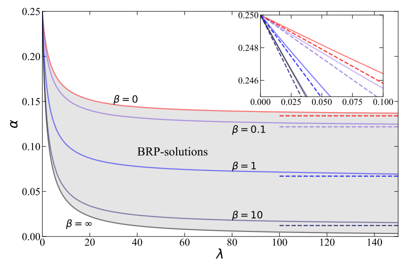
$\Lambda > 0$

ρ_{1R}

v_{1R}

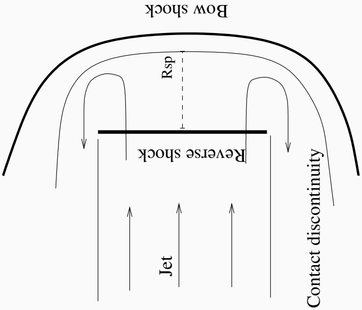
$\Lambda = 0$

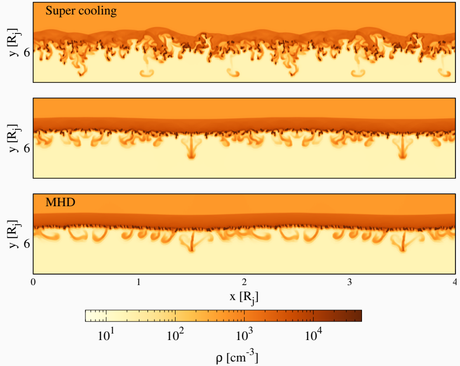
X_{ad} X_{c} X_{rad}



Density enhancement in the jet termination region

Particles accelerated in the adiabatic reverse shock can diffuse up to the dense layer/clumps and emit gamma rays via π^0-decay



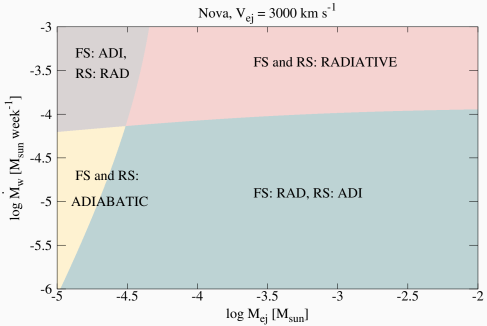


del Valle, Araudo & Suzuki-Vidal (2022)

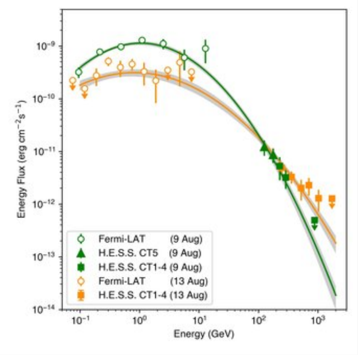
Nova outflows

Shock nature diagnostic

- The model-to-date to explain the gamma-ray emission from novae considers that particles are accelerated in radiative shocks (e.g. Metzger at al. 2015,2016)
- Adiabatic shocks are also possible in novae, and desirable for explaining TeV emission in RS Ophiuchi



del Valle, Araudo & Suzuki-Vidal (2022)



HEES Collaboration

MHD scaling for laboratory experiments

The scaling for laboratory experiments is in line with plasma conditions achievable in currently operating high-power laser facilities, opening the door to **new means for studying novae outflows never considered before**

Parameter	YSO jet	Lab	Novae	Lab
Length scale $[R] = \mathrm{cm}$	10^{16}	0.1	6×10^{13}	0.1
Density $[n] = \mathrm{cm}^{-3}$	10^{3}	5×10^{19}	10^{9}	5×10^{19}
Pressure $[P] = \mathrm{bar}$	10^{-13}	10^{5}	8×10^{-8}	8×10^{4}
Velocity $[v] = \mathrm{km\,s}^{-1}$	1000	700	1000	1000
Magnetic field $[B] = \mathrm{G}$	10^{-4}	10^{5}	10^{-2}	10^{4}
Time scale $[t] = \mathrm{s}$	10^{8}	10^{-9}	1.2×10^{6}	2×10^{-9}
Temperature $[T] = \mathrm{eV}$	50	1000	50	1000
Localisation parameter δ	10^{-3}	6×10^{-1}	10^{-7}	6×10^{-1}
Reynolds number Re	10^{10}	10^{4}	10^{9}	10^{4}
Peclet number Pe	10^{8}	~ 1	10^{8}	~ 1
Magnetic Reynolds number Re_M	10^{18}	10^{3}	10^{17}	10^{3}
Euler number Eu	11	8	11	11
Thermal plasma beta β	50	200	10^{4}	10^{4}

Conclusions

Conclusions

- YSO jets have enough kinetic power to accelerate TeV particles and destabilise non-resonant (Bell) modes
- **Particles accelerated in the adiabatic reverse shock diffuse up to the dense layer downstream of the radiative shock (or clumps in the mixing region)**
- Nova **RS Oph** was recently detected in gamma-rays. Our estimations indicate that the reverse shock is adiabatic and might accelerate particles up to high energies that could be responsible for the observed emission
- Parameters for scaled laboratory experiments for YSO jets and **nova outflows** are in line with plasma conditions achievable in current high-power laser facilities

31st Texas Symposium on Relativistic Astrophysics

gravity • cosmology • relativity

12 - 16 September 2022
Prague, Czech Republic

Invited Speakers include

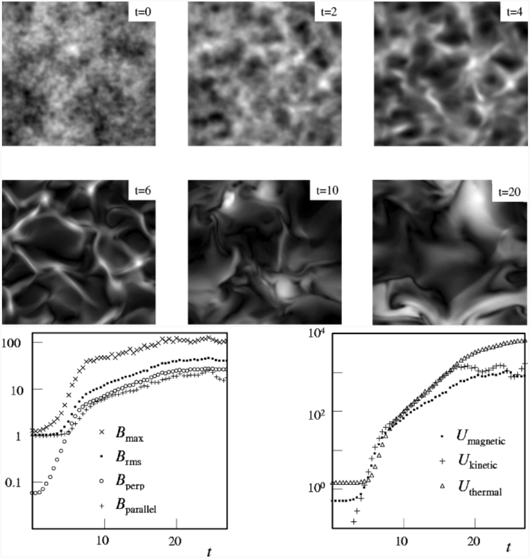
Herman Marshall
Ramesh Narayan
Felix Aharonian
Badri Krishnan
Elena Amato
Ivan Agullo
Tony Bell
Nanda Rea
Laura Blecha
Daniel Wang
Benoît Cerutti
Roger Blandford
Lavinia Heisenberg
Constantinos Skordis
Elisabete de Gouveia dal Pino

Questions?

Non-resonant hybrid (Bell) instabilities

Dispersion relation

$$\boxed{\omega^2 - k^2 v_\mathrm{A}^2 - k\zeta \frac{v_\mathrm{sh}^2}{r_\mathrm{gm}} = 0}$$

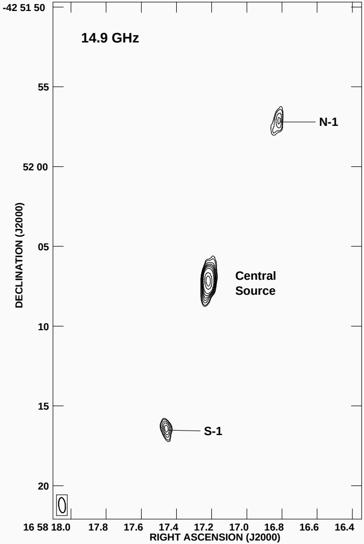


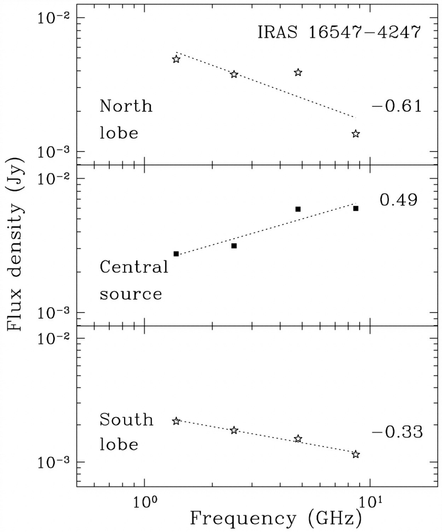
Bell (2004, 2005)

- Alfvén (resonant): $k^2 v_\mathrm{A}^2 > k\zeta \frac{v_\mathrm{sh}^2}{r_\mathrm{gm}}$
- Bell (non resonant): $k^2 v_\mathrm{A}^2 < k\zeta \frac{v_\mathrm{sh}^2}{r_\mathrm{gm}}$

  Magnetic field amplification!

Synchrotron emission from protostellar jets



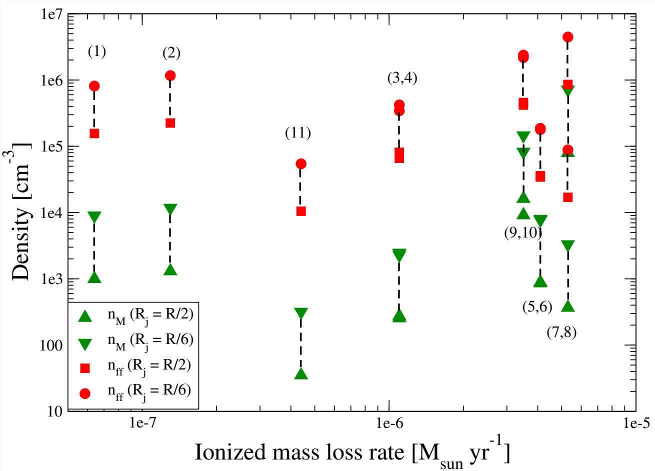


Rodríguez et al. (2005) Garay et al. (2003)

Jet density

Upper limit given by free-free emission ($\epsilon_{ff} < \epsilon_{\rm synchr}$):

$$\frac{n_{\rm ff}}{\rm cm^{-3}} \approx 1.4 \times 10^5 \left(\frac{d}{\rm kpc}\right) \left(\frac{S_\nu}{\rm mJy}\right)^{\frac{1}{2}} \left(\frac{R_{\rm j}}{10^{16}\rm cm}\right)^{-\frac{3}{2}} \left(\frac{v_{\rm sh}}{1000\,\rm km\,s^{-1}}\right)^{\frac{1}{2}}$$

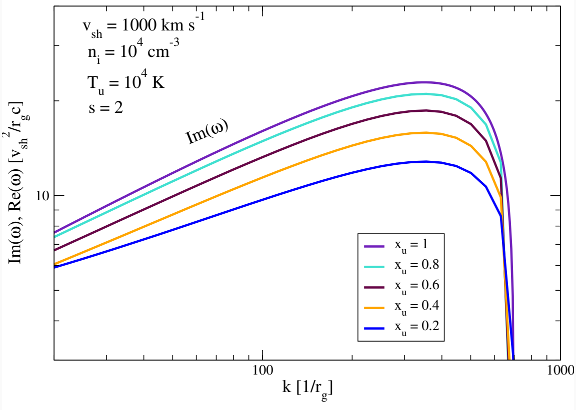


Bell instabilities in incompletely ionized YSO jets ($X_\mathrm{u} < 1$)

$\Gamma_{\mathrm{max,NR}}$ ius reduced due to ion-neutral collisions (Reville et al. 2007, Amato & Blasi (2010))

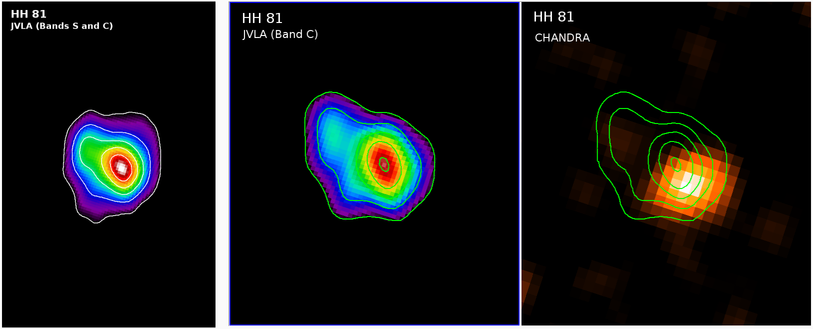
Ion-neutral collision frequency:

$$\frac{\nu_{\mathrm{in}}}{\mathrm{s}^{-1}} \simeq 8.9 \times 10^{-4} \left(\frac{T_\mathrm{u}}{10^4 \ \mathrm{K}} \right)^{0.5} \ \left(\frac{n_\mathrm{n}}{10^5 \mathrm{cm}^{-3}} \right),$$



HH 81 (Radio + X-rays)

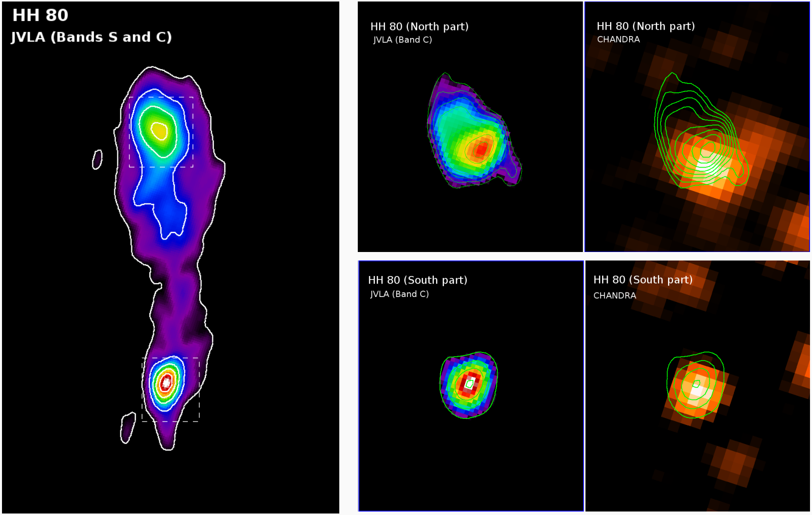
Shift between radio and X-ray emission (peak position)



Rodríguez-Kamenetzky et al. (2019)

HH 80 (Radio + X-rays)

Shift between radio and X-ray emission (peak possition)



Rodríguez-Kamenetzky et al. (2019)