Cosmic-ray acceleration and gamma-ray emission from protostellar jets

Anabella Araudo[1,2,3], Marco Padovani[4], Alexandre Marcowith[1]

(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
(4) Arcetri Astrophysical Observatory

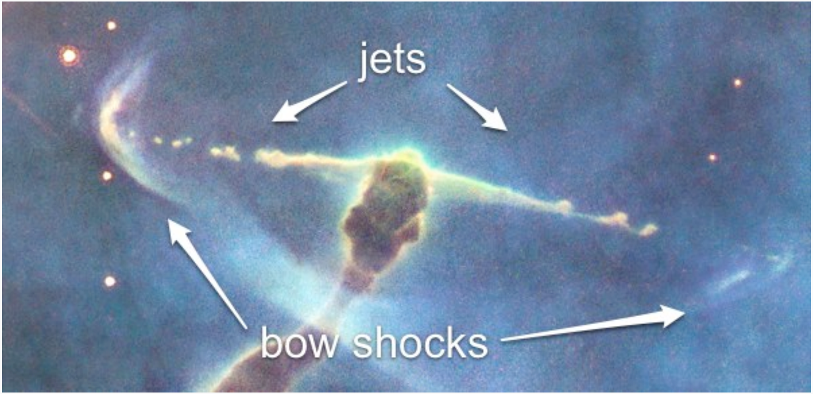
Table of contents

Introduction

Star forming regions

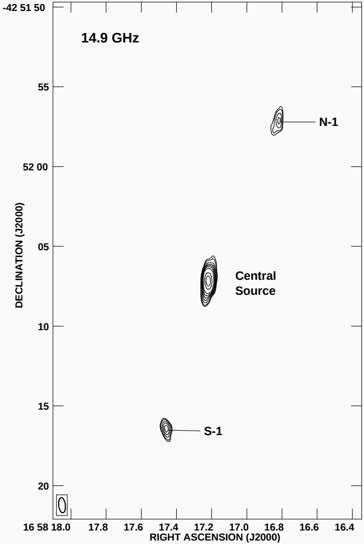
Protostellar jets

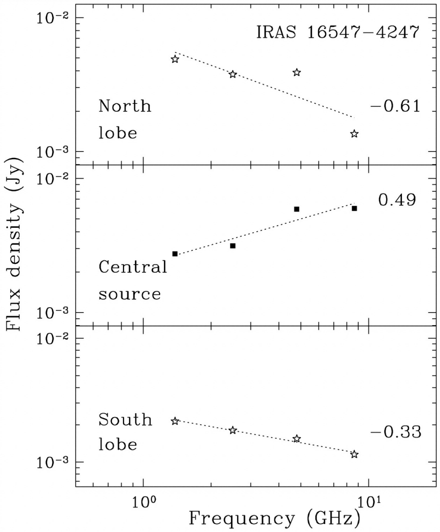
- Well known thermal emitters
- Increasing population of **non-thermal protostellar jets** (e.g. Purser et al. 2016)
- Jet velocities $v_\mathrm{j} \sim 300 - 1000$ km s^{-1}



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

Synchrotron emission from protostellar jets



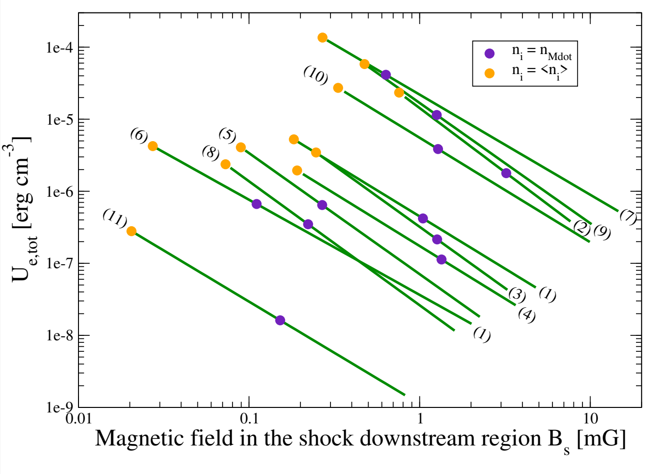


Rodríguez et al. (2005)

Garay et al. (2003)

Magnetic fields and non-thermal particles content

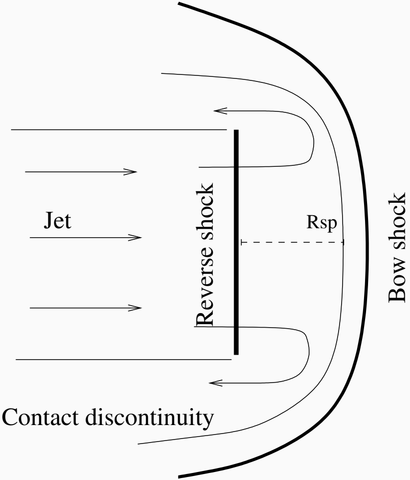
$$\frac{U_{\mathrm{e}}}{\mathrm{erg\,cm^{-3}}} \sim 5\times10^{-8}\left(\frac{d}{\mathrm{kpc}}\right)^{2}\left(\frac{S_{\nu}}{\mathrm{mJy}}\right)\left(\frac{R_{\mathrm{j}}}{10^{16}\mathrm{cm}}\right)^{-3}\left(\frac{\nu}{\mathrm{GHz}}\right)^{\frac{s-1}{2}}\left(\frac{B_{\mathrm{s}}}{\mathrm{mG}}\right)^{-\frac{s+1}{2}}$$



Magnetic field amplification by Bell instabilities

Jet termination region

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



$$\frac{n_\mathrm{j}}{\mathrm{cm}^{-3}} \approx 150 \left(\frac{\dot{M}_\mathrm{i}}{10^{-6}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}}\right) \left(\frac{v_\mathrm{j}}{1000\ \mathrm{km\,s}^{-1}}\right)^{-1} \left(\frac{R_\mathrm{j}}{10^{16}\,\mathrm{cm}}\right)^{-2}$$

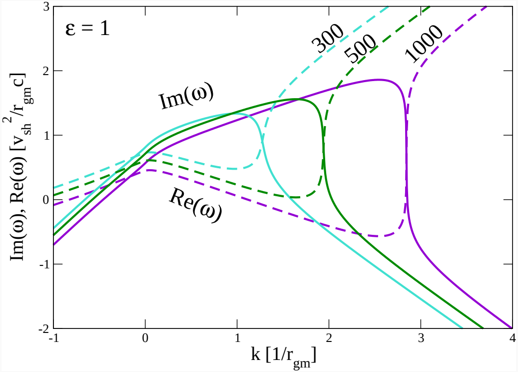
Bell instabilities in YSO jets

Condition for growing NR modes: $\zeta M_{\mathrm{A}}^2 > 1$

$$\zeta M_{\mathrm{A}}^2 \simeq 10^4 \left(\frac{\eta_p}{0.01}\right) \left(\frac{n_i}{10^3 \mathrm{cm}^{-3}}\right) \left(\frac{B_{\mathrm{j}}}{\mu \mathrm{G}}\right)^{-2} \left(\frac{v_{\mathrm{sh}}}{1000\,\mathrm{km\,s^{-1}}}\right)^3$$

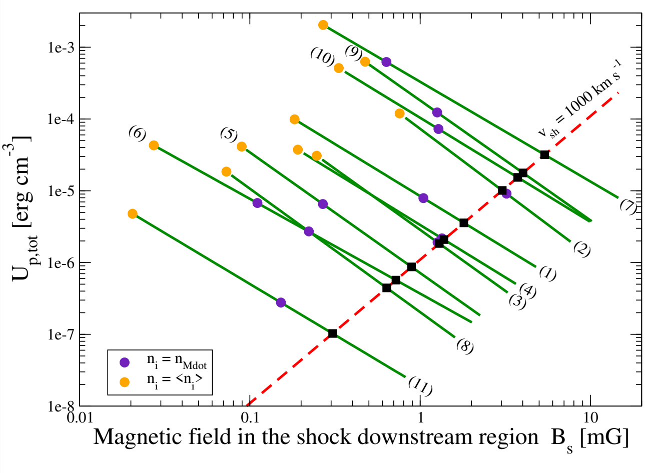
Maximum growth rate:

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



Magnetic field amplification in YSOs

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



Maximum energies and gamma-ray emission

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

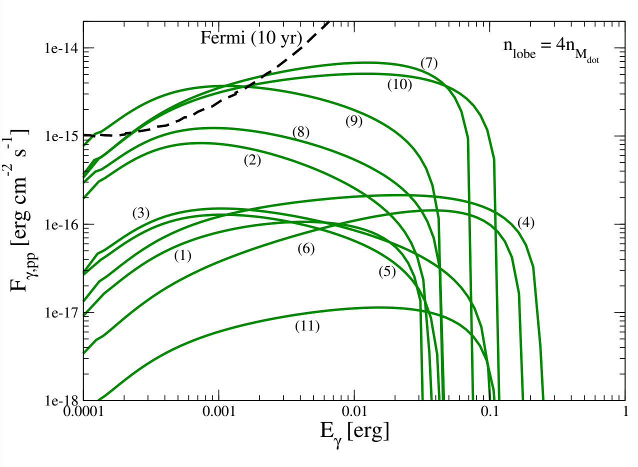
- $E_{p,\mathrm{max}}$ due to the **escape of particles upstream of the shock** $\Gamma_{\mathrm{max,NR}}(R_{\mathrm{j}}/v_{\mathrm{sh}}) > 5$ (Zirakashvili & Ptuskin 2008, Bell et al. 2013)
- For a distribution of protons $N_p \propto E_p^{-s}$

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

We find $E_{p,\mathrm{max}} \sim 0.1$ TeV for all the sources in our sample

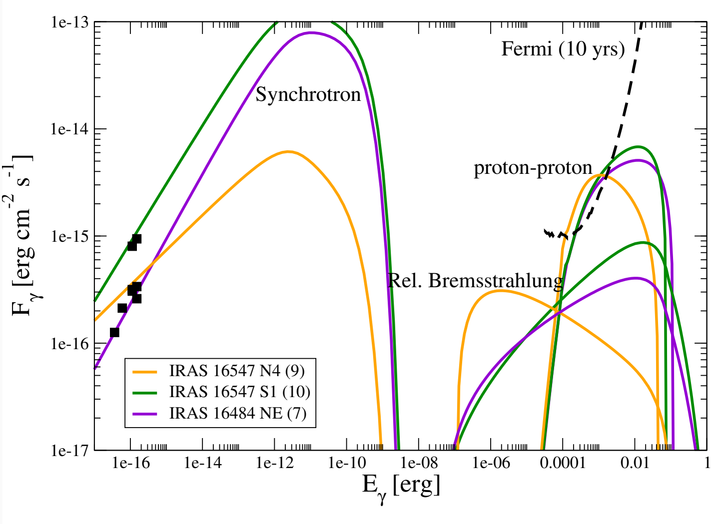
Gamma-ray emission

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



Araudo et al. (2021)

Gamma-ray emission

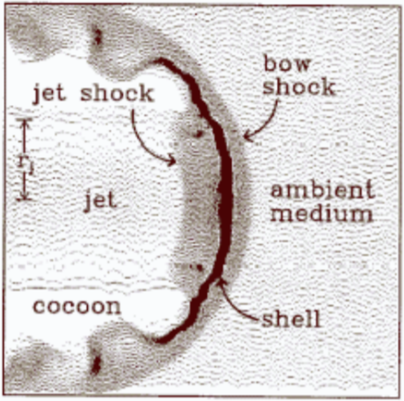


Araudo et al. (2021)

Density enhancement in the jet termination region

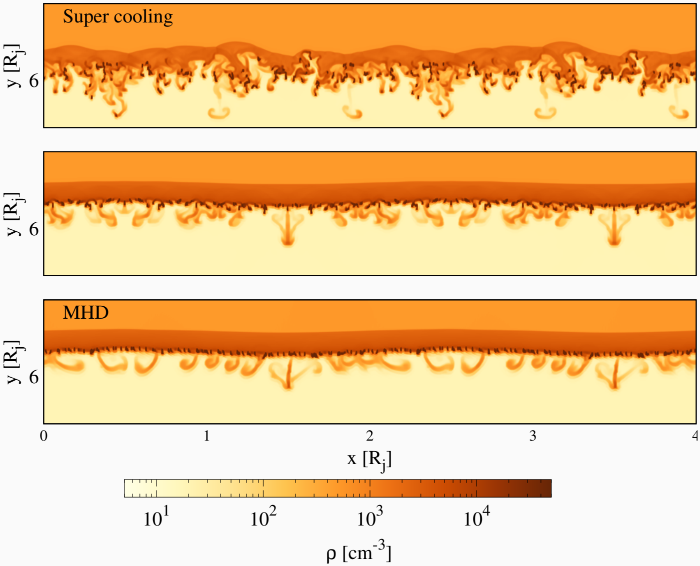
Rayleigh-Taylor mixing will increase the matter density in the emitter

$$\frac{n'_{\rm max}}{n_{\rm mc}} \sim 1000 \left(\frac{n_{\rm j}}{10^4\,{\rm cm^{-3}}}\right)^{\frac{1}{2}} \left(\frac{v_{\rm j}}{1000\,{\rm km\,s^{-1}}}\right) \left(\frac{B_{\rm mc,\perp}}{0.1{\rm mG}}\right)^{-1}$$



Blondin et al. (1989)

Density enhancement in the jet termination region



M.V. del Valle et al. (in preparation)

Conclusions

Conclusions

- Jets from high mass protostars (velocities ~ 1000 km s^{-1} and densities $\sim 100 - 10^4$ cm^{-3}) have enough kinetic power to accelerate particles and destabilise non-resonant (Bell) modes
- The maximum energy of protons (and electrons) is ~ 0.1 TeV
- We predict detectable gamma-ray fluxes from IRAS 16547-4247 and IRAS 16848-4603
- Rayleigh-Taylor mixing can make other protostellar jets detectable by Fermi and CTA

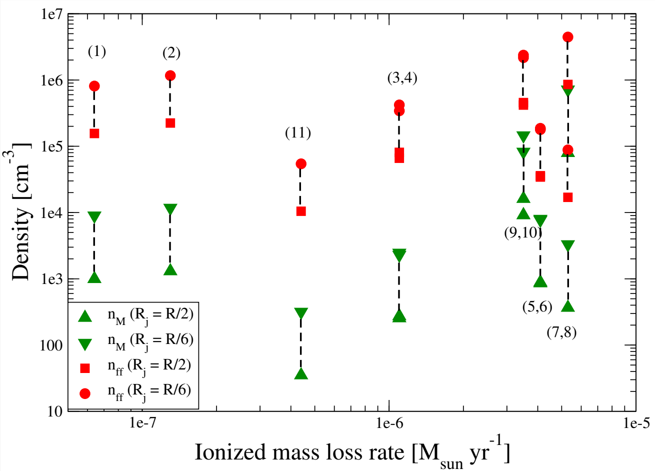
The detection of gamma rays from protostellar jets will be very important to study **diffusive shock acceleration** and **magnetic field amplification** in the high-density and low-velocity regime

Questions?

Jet density

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

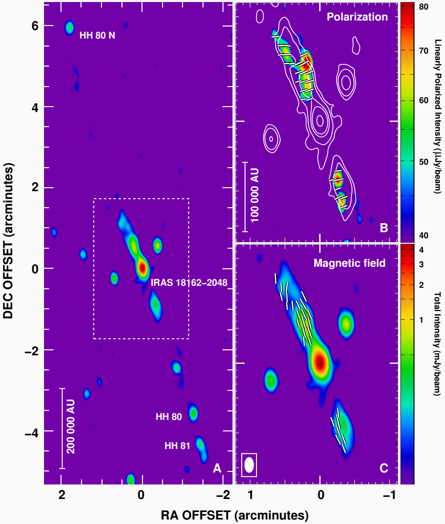
$$\frac{n_{\mathrm{ff}}}{\mathrm{cm}^{-3}} \approx 1.4 \times 10^{5} \left(\frac{d}{\mathrm{kpc}}\right) \left(\frac{S_\nu}{\mathrm{mJy}}\right)^{\frac{1}{2}} \left(\frac{R_{\mathrm{j}}}{10^{16}\mathrm{cm}}\right)^{-\frac{3}{2}} \left(\frac{v_{\mathrm{sh}}}{1000\,\mathrm{km\,s^{-1}}}\right)^{\frac{1}{2}}$$



Polarization measurements

Polarization measurement in IRAS 18162 (Herbig-Haro objects HH80 and HH81)

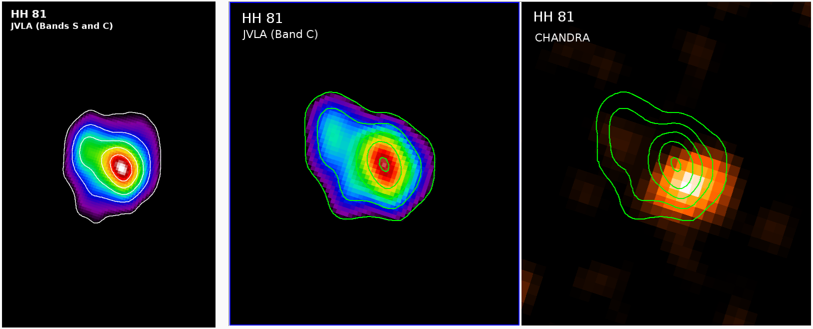
- Low spatial resolution VLA data (C-configuration)
- Magnetic field parallel to the jet axis
- Equipartition magnetic field ~ 0.2 mG



Carrasco-Gonzalez et al. (2010)

HH 81 (Radio + X-rays)

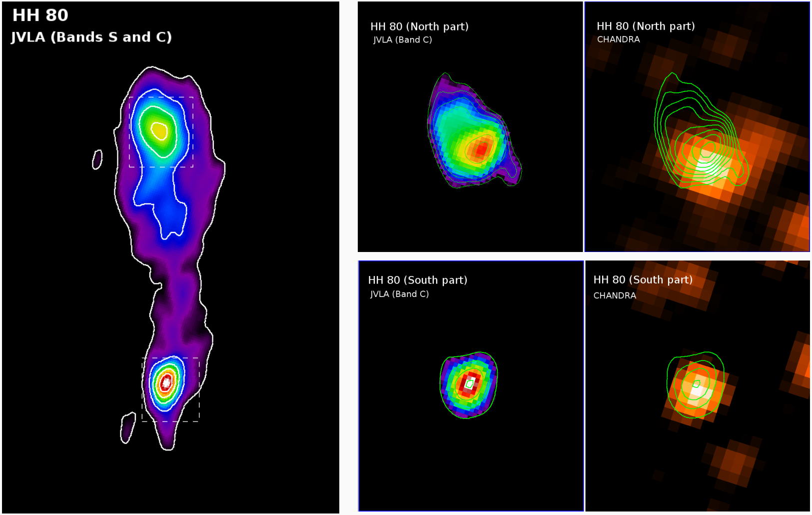
Shift between radio and X-ray emission (peak possition)



Rodríguez-Kamenetzky et al. (2019)

HH 80 (Radio + X-rays)

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



Rodríguez-Kamenetzky et al. (2019)

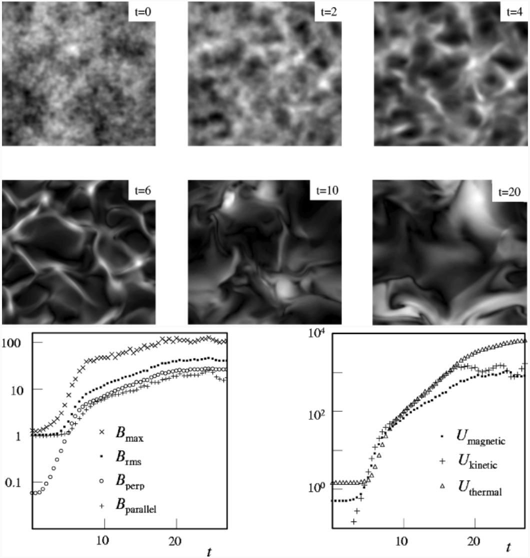
Cosmic-ray streaming instabilities

Dispersion relation

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

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

  Magnetic field amplification!



Bell (2004, 2005)