Collective gamma-ray emission from protostellar jets

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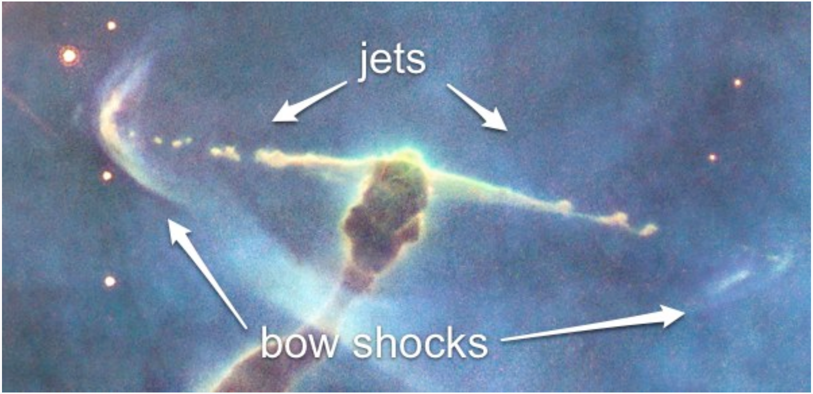
Star forming regions

Protostellar jets

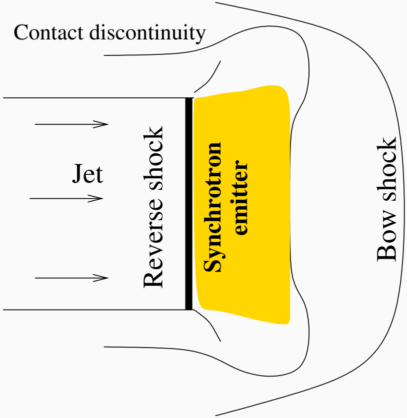
- Well known thermal emitters
- Increasing population of **non-thermal protostellar jets** (e.g. Purser et al. 2016)



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: $\eta_p = U_p/U_{\rm kin} \propto U_p/(n_{\rm j} v_{\rm j}^2)$



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

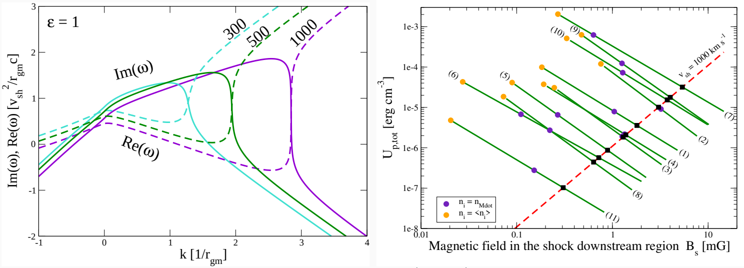
Bell instabilities in YSO jets

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

Maximum growth rate:

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

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



Araudo et al. (2021)

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

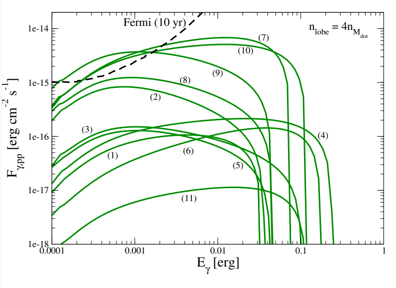
- $E_{p,\mathrm{max}}$ due to the **escape of particles upstream of the shock** $\Gamma_{\mathrm{max,NR}}(R_{\mathrm{j}}/v_{\mathrm{sh}}) > 5$ (Zirakashvili & Ptuskin 2008, Bell et al. 2013)
- For a distribution of protons $N_p \propto E_p^{-s}$

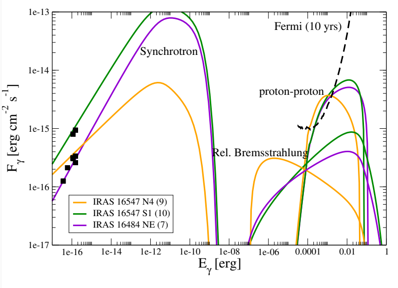
$$\frac{E_{p,\mathrm{max}}}{\mathrm{m_p c^2}} = \begin{cases} 70(2-s)\left(\frac{U_{p,\mathrm{tot}}}{10^{-5}\mathrm{erg\,cm^{-3}}}\right)\left(\frac{R_{\mathrm{j}}}{10^{16}\mathrm{cm}}\right)\left(\frac{n_i}{10^4\ \mathrm{cm^{-3}}}\right)^{-\frac{1}{2}} & s<2 \\ 70\log\left(\frac{E_{p,\mathrm{max}}}{\mathrm{GeV}}\right)^{-1}\left(\frac{U_{p,\mathrm{tot}}}{10^{-5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

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)

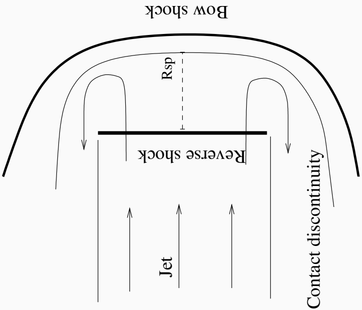


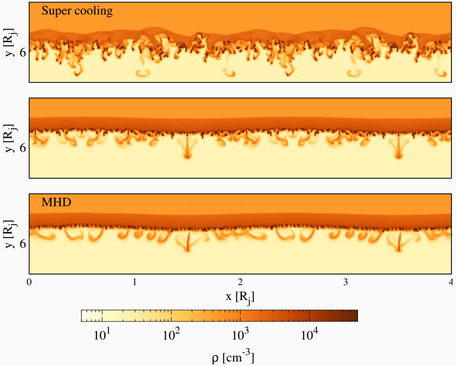


Araudo, Padovani & Marcowith (2021)

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[1]



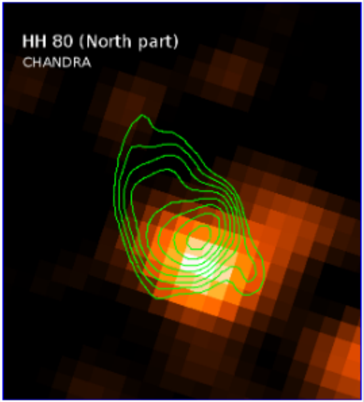


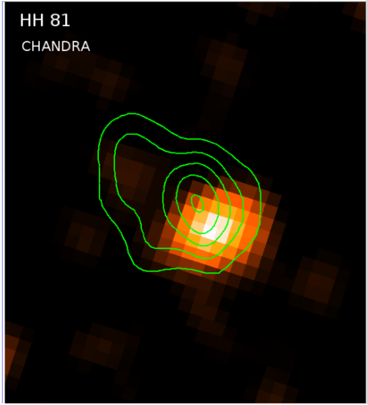
del Valle, Araudo & Suzuki-Vidal (2022)

[1] See Gintrand, Moreno, Araudo, Tikhonchuk & Weber (2021)

HH 80-81

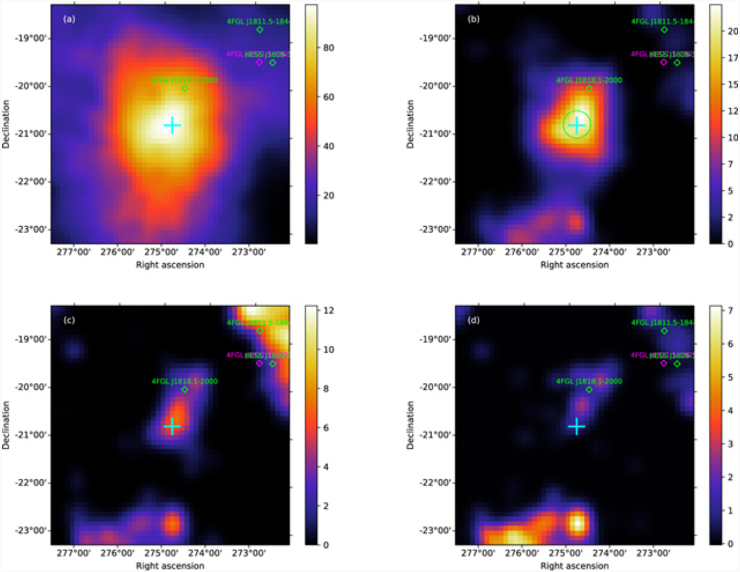
Shift between radio and X-ray emission (peak position) indicates that most probably the bow shock is radiative (thermal X-rays) and the reverse shock is adiabatic (synchrotron emitter)





Rodríguez-Kamenetzky et al. (2019)

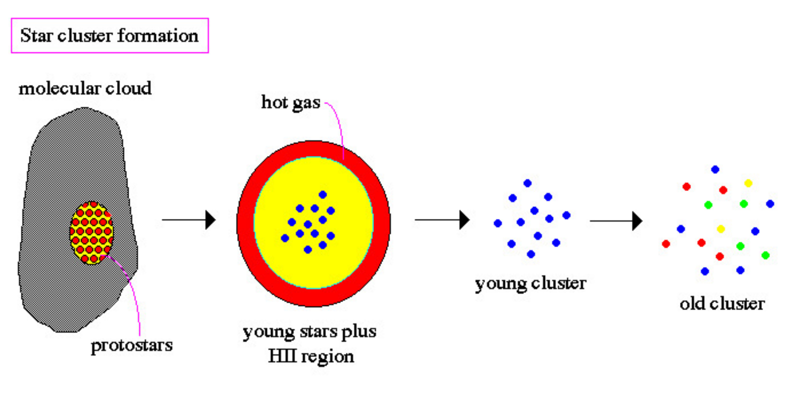
Detection of HH80-81 by Fermi?



Yan, Zhou & Zhang (2022)

Star forming regions

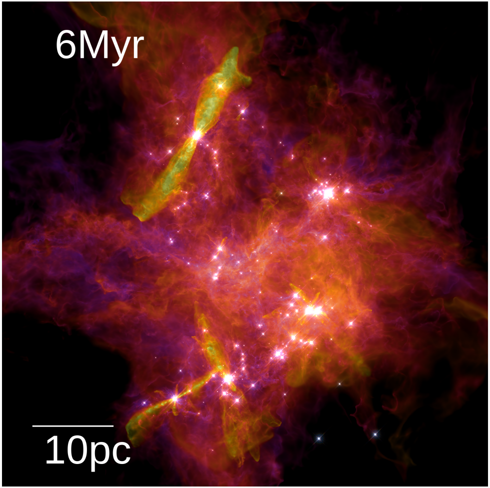
Contrary to low-mass protostars, high-mass protostars are far away and embedded in dense molecular clouds, making their detection more difficult.



Collective emission

In order to compute the collective gamma-ray emission we need to parameterize our model with the mass m of protostar

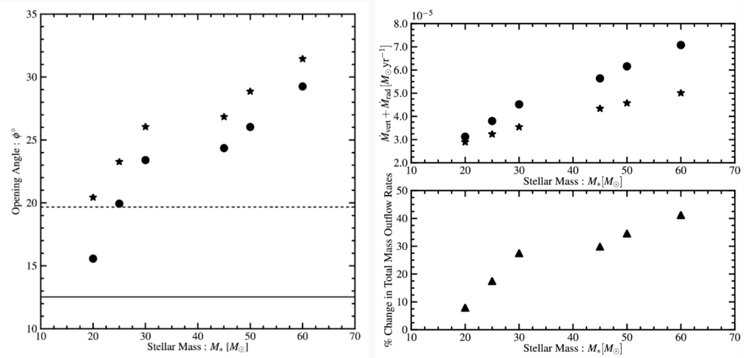
- Jet speed $v_{\rm jet}(m)$
  $v_{\rm jet} = 500$ km s^{-1}
- Jet mass loss rate
  $\dot{M}_{\rm j}(m) = \eta \dot{M}_{\rm acc}(m)$
  $\dot{M}_{\rm acc} = 10^{-3}$ M$_\odot$ yr^{-1}
- Protostellar mass function dN/dm



Guszejnov et al. (2020)

Jets from high mass protostars

- Radiation force from the central protostar is important for jet (de-)collimation
- $\dot{M}_{\rm acc} = 10^{-3}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$ (Hosokawa & Omukai, 2009)



Vaidya et al. (2018)

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)
- The collective emission of several protostellar jets embedded in a molecular cloud is crucial for these sources to be detected in the high-energy domain

Questions?

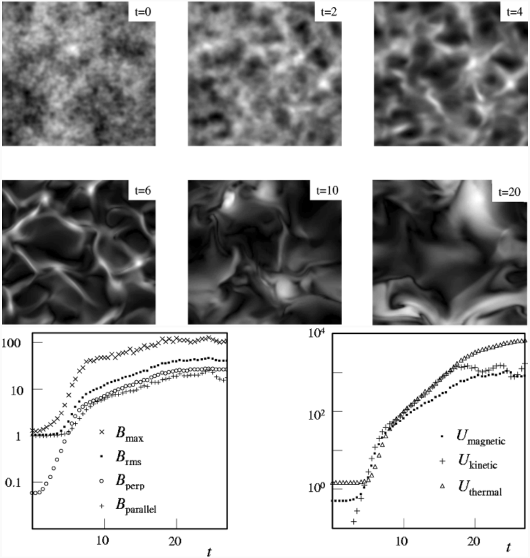
Non-resonant hybrid (Bell) instabilities

Dispersion relation

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

- 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)

Jet density

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

$$\frac{n_{\rm ff}}{\rm cm^{-3}} \approx 1.4\times10^5 \left(\frac{d}{\rm kpc}\right)\left(\frac{S_\nu}{\rm mJy}\right)^{\frac{1}{2}}\left(\frac{R_{\rm j}}{10^{16}\rm cm}\right)^{-\frac{3}{2}}\left(\frac{v_{\rm sh}}{1000\,\rm km\,s^{-1}}\right)^{\frac{1}{2}}$$