NON-THERMAL EMISSION FROM MASSIVE PROTOSTELLAR JETS: FROM RADIO TO GAMMA-RAYS

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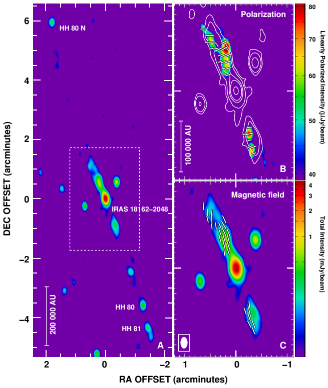
OUTLINE

JETS FROM YSOs

- Jets are supersonic and collimated flows of matter and electromagnetic fields.
- They emante from the central protostar and are stopped at $d \sim 1 - 10$ pc as a consequence of the interaction with the external medium (i.e. the molecular cloud).
- Models based on a disc- (Blandford & Payne, 1982) and a X-wind (Shu et al. 1994) has been proposed to explain the formation of protostellar jets.
- These jets are detected at different wavelengths, from radio to X-rays.

NON THERMAL EMISSION FROM YSOs JETS

- Non-thermal radio emission has been detected in a handfull of protostellar jets/HH objects.
- Most of them emanates from a massive protostar (e.g. HH 80-81, IRAS 16547-4247).
- Synchrotron radiation is produced by a population of relativistic electrons.
- These relativistics particles can produce also radiation at higher frecuencies.



Carrasco-Gonzalez et al. 2010

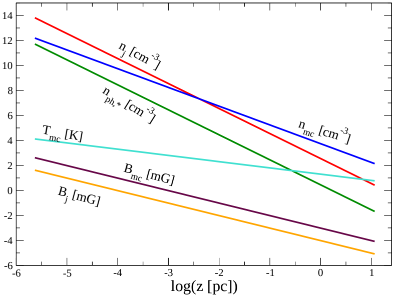
If particles have enough energy, γ-rays can be produced!

MODEL ASSUMPTIONS

- Jet kintic luminosity: $L_{\rm j} = \eta L_\star = 10^{36}\, \eta_{0.1} L_{\star,37}$ erg s^{-1}.
- Jet velocity: $v_{\rm j} = 500$ km s^{-1}.
- Jet density: $n_{\rm j} = 17 L_{\rm j,36}\, v_{\rm j,500}^{-3}\, \theta_{10}^{-2}\, (z/{\rm pc})^{-2}$ cm^{-3}.
- Jet magnetic field: $B_{\rm j} = 0.4 (z/{\rm pc})^{-1}$ mG ($U_{\rm B} = 10^{-3} U_{\rm kin}$).

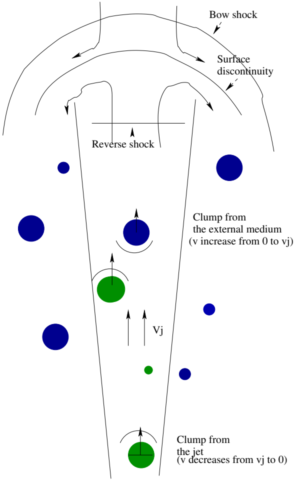
Molecular cloud:

- Density: $n_{\rm mc} = 10^3 (r/{\rm pc})^{-3/2}$ cm^{-3}
- Temperature: $T_{\rm mc} = 20 (r/{\rm pc})^{-0.5}$ K
  (Rodriguez & Garay 1990).
- Magnetic field: $B_{\rm mc} = (r/{\rm pc})^{-1}$ mG
  (Crutcher et al. 2011).



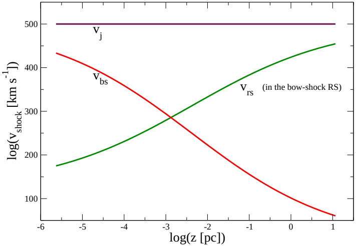
ESSENTIAL INGREDIENT OF THE MODEL: SHOCKS

- Jet-medium interaction: a bow shock in the molecular cloud and a shock (Mach disc) in the jet are formed.
- The (homogeneous) jet impact with an inhomogeneity of the cloud, and a bow shock is formed around the inhomogeneity.
- Clumps ejected from the jet base with velocity $v_c > v_j$ forms a bow shock in the jet.



JET TERMINATION SHOCKS

- $\chi_{\rm mc} = n_{\rm j}/n_{\rm mc}$.
- $v_{\rm bs} = v_{\rm j}/(1+\sqrt{1/\chi_{\rm mc}})$.
- $v_{\rm rs}|_{\rm bs} = v_{\rm j} - (3/4)v_{\rm bs}$.
- The bow shock is radiative ($l_{\rm th.cooling} < R_{\rm j}$).
- The reverse shock is adiabatic at $z \gtrsim 5\times10^{-2}$ pc.



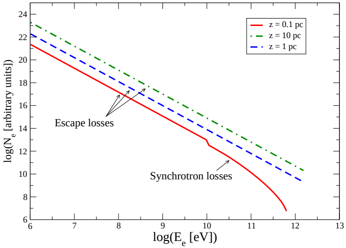
Then, particles can be accelerated (via Fermi I) up to high energies in the reverse shock.

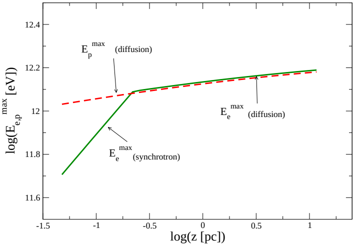
Hartigan 1988, Blondin et al. 1989, Güedel's talk

REVERSE SHOCK: PARTICLE ACCELERATION

- $L_{\rm nt} = \eta_{\rm nt}\, L_{\rm sh} \sim 10^{35} \left(\frac{\eta_{\rm nt}}{0.1}\right) \left(\frac{L_{\rm j}}{10^{36}{\rm erg\,s^{-1}}}\right)$ erg s^{-1}.
- $Q_{e,p} \propto E_{e,p}^{-2}$.
- We solve the following equation in the jet shocked region:

$$\frac{\partial N_{e,p}}{\partial t} = \frac{\partial}{\partial E_{e,p}}(\dot{E}_{e,p} N_{e,p}) - \frac{N_{e,p}}{\tau_{\rm esc}} + Q_{e,p}.$$

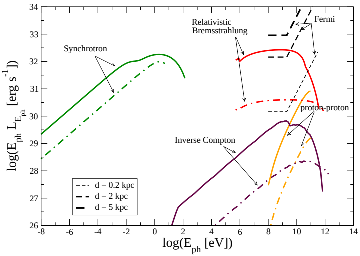


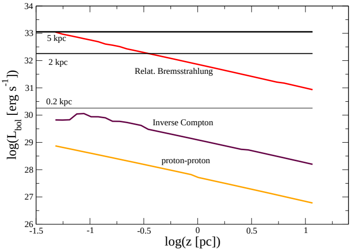


Reverse shock: non-thermal emission

- Spectral energy distributions at $z = 0.1$ and 10 pc.

- Bolometric luminosities in the Fermi range: 0.1 - 1 GeV.



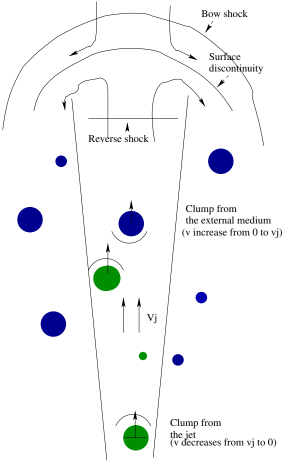


See Araudo et al. 2007 and Bosch-Ramon et al. 2010.

JET-CLUMP INTERACTION

- $\chi_{\rm c} = n_{\rm c}/n_{\rm j}$.
- $v_{\rm bs} = v_{\rm c}/(1 + 1/\sqrt{\chi_{\rm c}})$.
- $v_{\rm sc} = v_{\rm bs}/\sqrt{\chi_{\rm c}}$.
- The clump expands at the sound velocity: $\mathrm{d}r/\mathrm{d}t = C_{\rm s}$.
- The clump is accelerated up to $v_{\rm j}$ by the force exerted by the jet: $M_{\rm c}\frac{\mathrm{d}v_{\rm c}}{\mathrm{d}t} = \pm\rho_{\rm j}(v_{\rm bs} \pm v_{\rm j})^2\pi R_{\rm c}^2$.
- The clump can be disrupted by RT and KH instabilities.

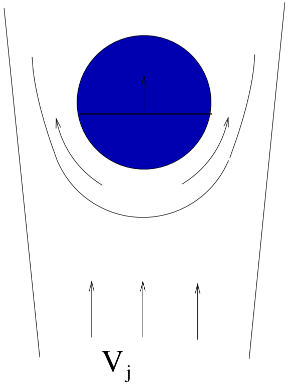
e.g. Klein et al. 1994, Pittard et al. 2010, Perucho & Bosch-Ramon 2012



CLUMP OF THE MOLECULAR CLOUD

Clump properties:

- $z_{\rm int} = 0.1$ pc.
- $R_{\rm c} = R_{\rm j}/2,\ 0.1\,R_{\rm j}$.
- $n_{\rm c} = 10\,n_{\rm mc} \rightarrow \chi_{\rm c} \sim 10$.
- $M_{\rm c} \sim 10^{-3},\ 10^{-5}\ {\rm M}_{\odot}$.
- $v_{\rm sc} \sim v_{\rm j}/\sqrt{\chi_{\rm c}} \sim 200$ km s^{-1}.
- $t_{\rm sc} \sim 10^{9},\ 2\times10^{8}$ s.
- $t_{\rm accel} > t_{\rm RT/KH} \gtrsim t_{\rm sc}$.
- Mixing between jet and ambient material.



After disruption, small bow shocks around the pieces can be formed, and particles can be also accelerated there.

CLUMP: PARTICLE ACCELERATION

- $L_{\rm nt} = \eta_{\rm nt}\left(\frac{R_{\rm c}}{R_{\rm j}}\right)^2 L_{\rm j} \sim 10^{35}\left(\frac{R_{\rm c}}{R_{\rm j}}\right)^2\left(\frac{\eta_{\rm nt}}{0.1}\right)\left(\frac{L_{\rm j}}{10^{36}{\rm erg\,s^{-1}}}\right)$ erg s^{-1}.
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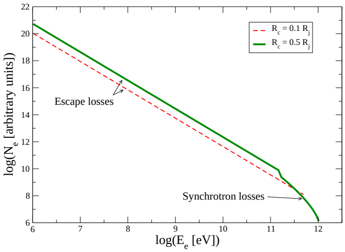
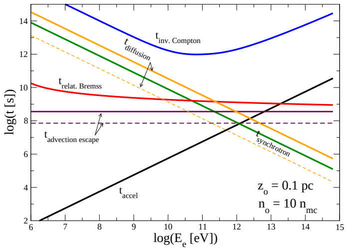
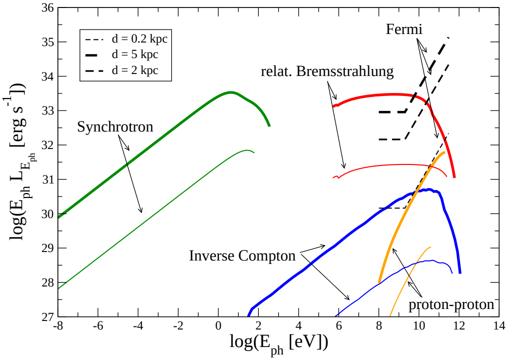




$E_e^{\rm max} \sim 0.5,\ 1$ TeV $\qquad E_p^{\rm max} \sim 0.5,\ 2.4$ TeV (diffusion)

CLUMP: NON-THERMAL EMISSION

- Relativistic Bremsstrahlung emission is detectable by Fermi.
- IC emission is detectable only in the case of large clumps.



SUMMARY AND CONCLUSIONS

- Synchrotron emission indicates the presence of relativistic electrons in jets from massive protostars.
- Electrons and protons can be accelerated in shocks produced by the jet interacting with the molecular cloud.
- If $v_{\mathrm{j}} \gtrsim 500$ km/s, these particles can reach enough energy to produce γ-rays.
- γ-ray emission from protostellar jets may be detected by the new generation of Cherenkov telescopes (e.g. CTA) and also by Fermi.
- There is an statistical correlation between some Fermi sources and massive protostars (Munar-Androver et al. 2011).

The detection of high-energy radiation open a new window to study the formation of massive stars, as well as the jet formation mechanism.

Future work

- To model the “two component” jet: homogeneous + clumpy.
- To study the dynamics (instabilities/lifetime) of clumps into the jet.
- To consider synchrotron emission as seed photons to inverse Compton scattering.
- To apply the model to particular sources (e.g. HH 80-81).