

Cosmic ray acceleration and gamma-ray emission from protostellar jets

Anabella Araudo,^{a,b,c,*} Marco Padovani^d and Alexandre Marcowith^a

^aLaboratoire Univers et Particules de Montpellier (LUPM) Université Montpellier, CNRS/IN2P3, CC72, place Eugène Bataillon, 34095

^bELI Beamlines, Institute of Physics, Academy of Sciences, 25241 Dolní Břežany, Czech Republic

^cAstronomical Institute, Academy of Sciences, Boční II 1401, CZ-141 00 Prague, Czech Republic

^dINAF-Osservatorio Astrofisico di Arcetri
Largo E. Fermi, 5 - 50125 Firenze, Italy

E-mail: anabella.araudo@eli-beams.eu

The detection of synchrotron radio emission from jets powered by massive protostars indicates the presence of relativistic electrons and magnetic fields of strength $\sim 0.3\text{--}5$ mG. We study diffusive shock acceleration and magnetic field amplification in protostellar jets with speed 1000 km s^{-1} . We show that the magnetic field in the synchrotron emitter can be amplified by the non-resonant hybrid (Bell) instability excited by the cosmic-ray streaming. By combining the synchrotron data with basic theory of Bell instability we estimate the magnetic field in the synchrotron emitter and the maximum energy of protons. Protons can achieve maximum energies ~ 0.1 TeV and emit γ rays in their interaction with matter fields. We predict detectable levels of γ rays in IRAS 16547-5247 and IRAS 16848-4603. The detection of this radiation by the Fermi satellite in the GeV domain and the forthcoming Cherenkov Telescope Array at higher energies may open a new window to study the formation of massive stars, as well as diffusive acceleration and magnetic field amplification in shocks with velocities of about 1000 km s^{-1} .

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1. Introduction

Stars are formed within dense molecular clouds, accreting matter onto the central protostar with the formation of a circumstellar disc and bipolar jets moving with speeds $v_j \sim 1000 \text{ km s}^{-1}$. Non-thermal radio emission has been detected in the termination region of several protostellar jets [1]. The detection of synchrotron radiation is an evidence that there is a population of mildly-relativistic or relativistic electrons in the jet, and strong magnetic fields.

- Magnetic fields in the synchrotron emitter in protostellar jets have strengths $B_s \approx 0.1\text{--}10 \text{ mG}$ (see Sect. 3). These values are larger than the expected magnetic field in the jet termination region, $B_j \approx 1\text{--}100 \text{ }\mu\text{G}$, requiring amplification of the magnetic field, given that compression by the shock does not produce strong enough fields.
- The energy density in non-thermal electrons and protons inferred from the synchrotron data is $\sim 10^{-8} \text{ erg cm}^{-3}$ (see Sect. 3). The cosmic-ray (CR) energy density in molecular clouds is poorly known, but it should be at least of the same order of the CR energy density in the interstellar medium, i.e. $\sim 10^{-12} \text{ erg cm}^{-3}$ [2]. Therefore, relativistic electrons and protons in the protostellar jets non-thermal lobes should be locally accelerated in the jet termination shocks.

In the present contribution we consider that show that the magnetic field in the synchrotron emitter of high-mass protostellar jets can be amplified by the streaming of CRs [3], as in supernova remnants [4] and jets in Active Galactic Nuclei [5]. By assuming that the number of non-thermal electrons and protons is the same, we find that the energy density in non-thermal protons is large enough to drive the Bell instability in the termination region of jets powered by the massive protostars IRAS 16547-4247 and 16484-4603. See [6] for a larger sample of sources, and a more detailed analysis.

If the non-resonant streaming instability is important and the magnetic field is amplified, the maximum energy of protons is determined by the amount of protons that escape from the shock upstream region [7, 8], giving maximum energies $\sim 0.1 \text{ TeV}$. Electrons diffusing in the turbulence generated by protons can achieve similar maximum energies. We model the gamma-ray emission and we show that detectable levels of gamma rays in the GeV domain are expected from the non-thermal lobes in the case studies.

2. The jet termination region

In the jet termination region, where the jet impacts against the ambient medium, a double shock structure (i.e. a working surface) is formed. In the particular case of light jets, where the jet (n_j) to molecular cloud (n_{mc}) density contrast is $\chi \equiv n_j/n_{\text{mc}} \ll 1$, the bow shock moves into the molecular cloud at a speed $v_{\text{bs}} \ll v_j$, and the reverse shock in the jet moves at $v_{\text{rs}} \sim v_j$. We consider that synchrotron emitting electrons are accelerated in the reverse shock with velocity $v_{\text{rs}} = 1000 \text{ km s}^{-1}$. The condition for the reverse shock to be adiabatic can be written as

$$\frac{v_{\text{rs}}}{\text{km s}^{-1}} > \frac{v_{\text{sh,ad}}}{\text{km s}^{-1}} \simeq 650 \left(\frac{n_j}{10^4 \text{ cm}^{-3}} \right)^{\frac{2}{9}} \left(\frac{R_j}{10^{16} \text{ cm}} \right)^{\frac{2}{9}}, \quad (1)$$

and the jet ion density can be estimated as [9]

$$\frac{n_j}{\text{cm}^{-3}} \approx 150 \left(\frac{\dot{M}_i}{10^{-6} M_\odot \text{ yr}^{-1}} \right) \left(\frac{v_j}{1000 \text{ km s}^{-1}} \right)^{-1} \left(\frac{R_j}{10^{16} \text{ cm}} \right)^{-2}. \quad (2)$$

The ionized jet mass loss rate $\dot{M}_i \propto v_j$ is assumed to be constant along the jet and then n_j turns out to be independent of the jet velocity. By considering $\dot{M}_i = 5.6 \times 10^{-6}$ and $3.5 \times 10^{-6} M_\odot \text{ yr}^{-1}$ for IRAS 16484-4603 and IRAS 16547-4247, respectively [1], and assuming $R_j = R/2$ we obtain the values of n_j listed in Table 1. By inserting Eq. (2) in Eq. (1) we find that $v_{\text{sh,ad}} \propto R_j^{-2/9}$, also listed in Table 1. We note that n_j is a rough estimation of the jet ion density given the uncertainties in the values of \dot{M}_i and R_j . Nevertheless, the derived jet density is likely lower than the typical density values of $\sim 10^5 \text{ cm}^{-3}$ in the molecular clouds where massive stars form [10] giving $\chi < 1$.

3. Cosmic Ray population

Non-thermal electrons follow a power-law distribution $N_e = K_e E^{-s}$, where $s = 2\alpha + 1$. The normalization factor K_e is determined from the measured synchrotron flux S_ν at a particular frequency ν , giving

$$\frac{K_e}{\text{erg}^{s-1} \text{ cm}^{-3}} \approx 1.6 \times 10^{-9} \xi_K(s) \left(\frac{d}{\text{kpc}} \right)^2 \left(\frac{S_\nu}{\text{mJy}} \right) \left(\frac{R}{10^{16} \text{ cm}} \right)^{-3} \left(\frac{\nu}{\text{GHz}} \right)^{\frac{s-1}{2}} \left(\frac{B_s}{\text{mG}} \right)^{-\frac{s+1}{2}}, \quad (3)$$

where B_s is the magnetic field in the synchrotron emitter, i.e. mostly coming from the shock downstream medium, and

$$\xi_K(s) \approx 10^{-3.55(s-2)} \frac{\Gamma\left(\frac{s+5}{4}\right) \Gamma\left(\frac{3s-1}{12}\right) \Gamma\left(\frac{3s+19}{12}\right)}{\Gamma\left(\frac{s+7}{4}\right) (s+1)}. \quad (4)$$

The energy density in non-thermal electrons reads

$$\frac{U_{e,\text{tot}}}{\text{erg cm}^{-3}} \approx 5 \times 10^{-8} \xi_K(s) \left(\frac{f_e}{10} \right) \left(\frac{\nu}{\text{GHz}} \right)^{\frac{s-1}{2}} \left(\frac{\epsilon_{\text{syn},\nu}}{10^{-30} \text{ erg s}^{-1} \text{ cm}^{-3} \text{ Hz}^{-1}} \right) \left(\frac{B_s}{\text{mG}} \right)^{-\frac{(s+1)}{2}}. \quad (5)$$

The energy density in protons is $U_{p,\text{tot}} = a U_{e,\text{tot}}$, where $a = (m_p/m_e)^{(s-1)/2} f_p/f_e$ and $f_{e,p} \sim E_{e,p\text{max}}^{2-s}/(2-2)$ and $(m_{e,p}c^2)^{2-s}/(s-2)$ when $s < 2$ and > 2 , respectively. The non-thermal energy density is $U_{\text{nt}} = (1+a)U_{e,\text{tot}}$, and then the magnetic field in equipartition with non-thermal electrons and protons is $B_{\text{eq}} = [(1+a)U_{e,\text{tot}}8\pi]^{0.5}$. In Table 2 we list the values of s , a , and B_{eq} for all the sources in Table 1 and considering $E_{e,\text{max}} = 0.1 \text{ TeV}$ in f_e . (Note however that the dependence on $E_{e,\text{max}}$ is negligible.)

We define the total proton acceleration efficiency $\eta_{p,\text{tot}} = U_{p,\text{tot}}/U_{\text{kin}}$, where $U_{\text{kin}} = n_j v_j^2/2$ is the jet kinetic energy density. The acceleration efficiency η_p of protons with particular energy E_p is defined as $\eta_p = \eta_{p,\text{tot}}/f_p$. These protons can drive a current that combined with small perturbations present in the magnetic field can excite NR waves [3] when

$$\frac{v_{\text{sh}}}{\text{km s}^{-1}} > 128 \left(\frac{\eta_p}{0.02} \right)^{-\frac{1}{2}} \left(\frac{B_j}{10 \mu\text{G}} \right) \left(\frac{n_j}{10^4 \text{ cm}^{-3}} \right)^{-\frac{1}{2}}. \quad (6)$$

Table 1: Observed and derived parameters of non-thermal lobes associated with MYSOs. From left to right we list the name of the source and the non-thermal component in the jet, the observed frequency ν , the measured flux density S_ν , the radio spectral index α , the average linear size R , the synchrotron emissivity ϵ_{synchr} , the lower limit on the shock velocity $v_{\text{sh,ad}}$ and the density n_j .

Source	ν [GHz]	S_ν [mJy]	α	R [cm]	ϵ_{synchr} [erg cm ⁻³ s ⁻¹ Hz ⁻¹]	$v_{\text{sh,ad}}$ [km s ⁻¹]	n_j [cm ⁻³]
G339.8838 NE	9	2.36	0.39	8.1×10^{15}	1.3×10^{-28}	842	7.9×10^4
G343.1261 N4	17	1.80	0.67	1.0×10^{16}	3.2×10^{-29}	674	1.6×10^4
G343.1261 S1	17	4.72	0.45	1.0×10^{16}	3.8×10^{-29}	633	9.2×10^3

The regime dominated by Alfvén turbulence was studied by [11, 12] in the context of low mass protostars, where the jet typical velocities are $\sim 100 \text{ km s}^{-1}$. The important aspect of destabilizing perturbations in resonance with CRs is that the scattering process is more efficient. However, this does not guarantee to have a strong amplification.

4. Magnetic field amplification by Bell instabilities

Magnetic field strengths $B_s \approx 0.1\text{--}10 \text{ mG}$ are larger than the expected magnetic field in the jet termination region. In this study we consider the magnetic field amplification by the Bell instability in the non-linear case [3, 13]. The (total) saturated magnetic field $B_{\text{sat,NR}}$ immediately upstream of the shock is estimated by considering the total proton acceleration efficiency $\eta_{p,\text{tot}}$, which gives

$$\frac{B_{\text{sat,NR}}}{\text{mG}} \approx 1.2 \left(\frac{\eta_{p,\text{tot}}}{0.1} \right)^{\frac{1}{2}} \left(\frac{n_i}{10^4 \text{ cm}^{-3}} \right)^{\frac{1}{2}} \left(\frac{v_{\text{sh}}}{1000 \text{ km s}^{-1}} \right)^{\frac{3}{2}}. \quad (7)$$

In the shock downstream region, the turbulent upstream magnetic field is compressed by a factor $r_B = \sqrt{(2r^2 + 1)}/3 \approx 3.3$ when the shock compression ratio is $r = 4$ [e.g. 7, 14]. Therefore, the amplified field downstream of the shock is $B_{\text{sat,d}} = r_B B_{\text{sat,NR}}$. On the other hand, the magnetic field in the synchrotron emitter B_s , i.e. mostly coming from the shock downstream region, is a function of the energy density in non-thermal electrons. By assuming that $B_{\text{sat,d}} = B_s$ we find that $B_{\text{sat,d}}/B_{\text{eq}} \sim 0.4(v_{\text{sh}}/1000 \text{ km s}^{-1})^2/(s + 5)$.

5. Gamma-ray emission

The maximum energy of protons is determined by the amount of protons that escape from the shock upstream region [7, 8]. Given that only the most energetic protons can penetrate far upstream from the shock and amplify the magnetic field in the shock precursor, the available time to accelerate these particles is $\sim 5/\Gamma_{\text{max,NR}}(E_{p,\text{max}})$, where

$$\frac{\Gamma_{\text{max,NR}}}{\text{s}^{-1}} \sim 2.6 \times 10^{-5} \left(\frac{\eta_p}{0.02} \right) \left(\frac{v_{\text{sh}}}{1000 \text{ km s}^{-1}} \right)^3 \left(\frac{n_i}{10^4 \text{ cm}^{-3}} \right)^{\frac{1}{2}} \left(\frac{E_{p,\text{max}}}{\text{GeV}} \right)^{-1}. \quad (8)$$

Table 2: From left to right we list the source names, the relativistic electrons and protons energy power-law slope $s = 2\alpha + 1$, the total protons-to-electrons energy density ratio (a , for the case $E_{e,\max} = E_{p,\max} = 1$ TeV), the equipartition magnetic field (B_{eq}), the amplified field in the shock downstream region ($B_{\text{sat,NR}}$), the total energy density in protons ($U_{p,\text{tot}}$) and their acceleration efficiency ($\eta_{p,\text{tot}}$), and the protons maximum energy ($E_{p,\max}$).

Source	s	a	B_{eq} [mG]	$B_{\text{sat,NR}}$ [mG]	$U_{p,\text{tot}}$ [erg cm ⁻³]	$\eta_{p,\text{tot}}$	$E_{p,\max}$ [TeV]
G339.8838 NE	1.78	15.06	14.6	1.63	3.2×10^{-5}	0.05	0.28
G343.1261 N4	2.34	10.80	10.2	1.22	1.7×10^{-5}	0.13	0.17
G343.1261 S1	1.89	63.07	9.93	1.13	1.5×10^{-5}	0.20	0.43

is the maximum growth rate of the Bell instability driven by protons with energy $E_{p,\max}$. By equating $5/\Gamma_{\text{max,NR}}(E_{p,\max}) = R_j/v_{\text{sh}}$ we find [8, 15]

$$\frac{E_{p,\max}}{m_p c^2} = \begin{cases} 70(2-s) \left(\frac{U_{p,\text{tot}}}{10^{-5} \text{erg cm}^{-3}} \right) \left(\frac{R_j}{10^{16} \text{cm}} \right) \left(\frac{n_i}{10^4 \text{cm}^{-3}} \right)^{-\frac{1}{2}} & s < 2 \\ 70 \log \left(\frac{E_{p,\max}}{\text{GeV}} \right)^{-1} \left(\frac{U_{p,\text{tot}}}{10^{-5} \text{erg cm}^{-3}} \right) \left(\frac{R_j}{10^{16} \text{cm}} \right) \left(\frac{n_i}{10^4 \text{cm}^{-3}} \right)^{-\frac{1}{2}} & s = 2 \\ \left[70(s-2) \frac{1}{m_p c^2} \left(\frac{U_{p,\text{tot}}}{10^{-5} \text{erg cm}^{-3}} \right) \left(\frac{R_j}{10^{16} \text{cm}} \right) \left(\frac{n_i}{10^4 \text{cm}^{-3}} \right)^{-\frac{1}{2}} \right]^{\frac{1}{s-1}} & s > 2 \end{cases} \quad (9)$$

Values of $E_{p,\max}$ for the non-thermal lobes in our study are listed in Table 2 for the case $v_{\text{sh}} = 1000 \text{ km s}^{-1}$ and $R_j = R/2$. The condition $\Gamma_{\text{max,NR}}(E_{p,\max})R_j/v_{\text{sh}} > 5$ was introduced by [8] for the case of SNR and where they considered the size of the spherical shock (instead of R_j). However, [7] found a similar expression for planar non-relativistic shocks.

Electrons are not the main drivers of the turbulence and can be considered as test particles. If the Bell instability gets into the non-linear phase, we can expect to have the turbulence coherence length ℓ_c limited by the Larmor radius of the protons at the maximum energy $E_{p,\max}$ in the amplified field B_s . If we assume that the maximum electrons energy $E_{e,\max}$ exceeds $E_{p,\max}$, then the turbulence experienced by electrons will be in the small-scale turbulence regime and the diffusion coefficient would be $\propto D_{\text{Bohm}}(E_{p,\max}, B_s)(E_e/E_{p,\max})^2$. This rapid increase with the energy would limit $E_{e,\max}$ to $E_{p,\max}$ unless radiative losses dominate and limit it to smaller values. Then, one should expect to have $E_{e,\max} \leq E_{p,\max}$.

TeV electrons and protons can emit gamma-rays by their interaction with ambient cold protons through relativistic Bremsstrahlung and proton-proton (pp) collisions¹. The distribution of relativistic protons in the jet hotspot is $N_p = K_p E_p^{-s}$, where $K_p = K_e (m_p/m_e)^{(s-1)/2}$. In Table 2 we list the values of K_e and K_p (with $B_s = 3.3B_{\text{sat,NR}}$). We compute the spectral energy distribution (SED) in the one-zone model approximation. We assume that the volume of the γ -ray emitter is the same as the synchrotron emission volume and that the thermal ion density in the lobe is $4n_j$. We plot in Fig. 1 the SED including proton-proton collisions, synchrotron emission and relativistic Bremsstrahlung and using the formulation in [16] and [17]. We assume $E_{e,\max} = E_{p,\max}$ as it is

¹Note that in the jet termination region, at $\sim 10^4$ AU from the central protostar, the stellar photon field is very diluted and therefore the Inverse Compton scattering is not expected to be very relevant.

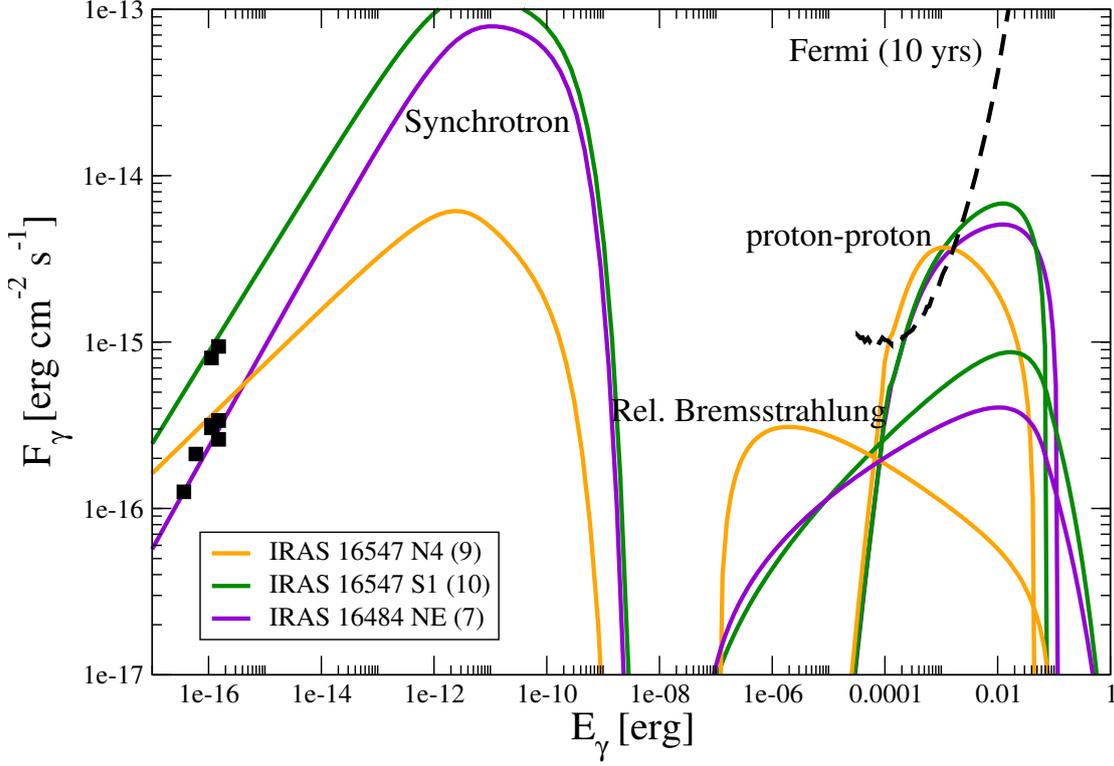


Figure 1: Spectral energy distribution for the three hotspots. Black squares indicate synchrotron data [1] and the black dashed line represent the Fermi sensitivity for 10 years of observation.

calculated in Eq. (9). We can see that the predicted emission is detectable by *Fermi*-LAT after 10 years of observation (with 5σ -confidence).

6. Conclusions

The detection of synchrotron emission from jets powered by high-mass protostars indicates that electrons are in-situ accelerated. Magnetic fields $B_s \sim 0.3 - 5$ mG are needed to explain the synchrotron radio flux. These large values of B_s are difficult to explain by a simple compression in an adiabatic strong shock at the jet termination region, at ~ 0.1 pc from the central protostar. In the present contribution we focus on magnetic field amplification by streaming instabilities.

CR streaming instabilities can excite the NR (Bell) instability which produces perturbations at scales much smaller than r_g [3]. Bell's instability can amplify small perturbations in the magnetic field up to values much larger than the unperturbed jet magnetic field B_j when the condition in Eq. (6) is satisfied. We remark that large ion densities in a non-completely ionized protostellar jet would increase the ion-neutral collisions and Alfvén waves can be damped [18]. Conversely, Bell modes are not as heavily damped, although the maximum growth rate decreases [19].

By assuming that the large magnetic field in the synchrotron emitter (B_s) is due to amplification through the Bell's instability and fixing $v_{sh} = 1000$ km s $^{-1}$ we estimate $B_s \sim 0.4B_{eq}$ and the the

proton acceleration efficiency $\eta_{p,\text{tot}} \sim 0.1$. By knowing $\eta_{p,\text{tot}}$ and B_s we estimate the maximum energy of protons accelerated in the jet reverse shock and the γ -ray emission that they produce. We find that having a density of $4n_j$ in the non-thermal emitter is high enough to reach detectable levels of γ rays with *Fermi* in IRAS 16547 N4, IRAS 16547 S1, and IRAS 16848 NE, as we show in Fig. 1. Although there is no claim of detection of these sources by *Fermi*, we expect that our result will motivate a future study on the *Fermi* data at the location of these sources. In addition, these sources will be perfect targets for a point-source mode. We also note that mixing due to dynamical instabilities can significantly enhance the density of targets in the lobes. The very dense shell formed downstream of the radiative bow shock is unstable and fragmented in clumps with density ~ 100 – 1000 times the density of the molecular cloud. By achieving $F_{\gamma,pp} \sim 5 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ at 0.1 TeV, CTA will be of great importance to measure the cut-off of the spectrum. Also, the spatial resolution of CTA is expected to be better than *Fermi*. The detection of γ rays from protostellar jets will open a new window to study stellar formation, as well as the efficiency of DSA in the high density ($n_j \sim 10^3 - 10^4 \text{ cm}^{-3}$) and low velocity ($v_{\text{sh}} \sim 1000 \text{ km s}^{-1}$) regime. In particular, the detection of diffuse gamma-ray emission in molecular clouds where MYSOs are embedded will be a piece of evidence of proton acceleration in protostellar jets.

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