Jets from massive protostars as gamma-ray sources: the case of IRAS 18162-2048

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Abstract. Protostellar jets are present in the later stages of the stellar formation. Non-thermal radio emission has been detected from the jets and hot spots of some massive protostars, indicating the presence of relativistic electrons there. We are interested in exploring if these non-thermal particles can emit also at γ-rays. In the present contribution we model the non-thermal emission produced in the jets associated with the massive protostar IRAS 18162-2048. We obtain that the γ-ray emission produced in this source is detectable by the current facilities in the GeV domain.

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INTRODUCTION

Massive stars are formed within dense molecular clouds, accreting matter onto the central protostar with the formation of a circumstellar disc and forming bipolar jets and molecular outflows. In the last decade a handful of jets that emanate from massive protostars have been detected at radio wavelengths. In most of the cases, this radio emission has a negative spectral index (α), indicating the non-thermal nature of it. However, only in the case of the jet associated with the source IRAS 18162−2048, polarization of radio emission has been measured [1] confirming that the radiation is produced by the synchrotron process.

The jets of the source IRAS 18162-2048

The famous Herbig-Haro (HH) objects called HH80-81 are the south component of a system of several radio sources, located at a distance of ~ 1.7 kpc. The central source has been identified with the luminous ($L_\star = 1.7 \times 10^4 L_\odot$) protostar IRAS 18162−2048, and HH80-N is the northern counterpart of HH80−81. The velocity of the jet close to the protostar has been estimated to be as large as $v_{\rm j} \sim 1400$ km s^{-1} [2], whereas HH 80 and HH 81 (located at $z \sim 2.5$ pc from IRAS 18162-2048) are moving with slower velocity, ~ 150 km s^{-1}, and HH80-N appears to be at rest. Radio observations [2] show that the central source has a spectral index $\alpha \sim 0.1$, typical of free-free emission, whereas HH80−81 and HH80-N are likely non-thermal sources, with $\alpha \sim -0.3$. Between the central protostar and the HH-objects there is a chain of bright thermal and non-thermal knots. In particular, at a distance $z_{\rm p} = 0.5$ pc from the central protostar, an elongated structure of polarized radio emission has been recently detected through observations carried out with the Very Large Array (VLA) [1]. The detection of synchrotron radiation is evidence that there is a population of relativistic electrons in the source. These relativistic particles in the complex environment of the massive molecular cloud where the protostar is being formed can produce high-energy radiation through a variety of processes. In the present contribution we model the non-thermal emission produced in the polarized jet of IRAS 18162-2048, from radio to γ-rays, at a distance $z_{\rm p} = 0.5$ pc from the central protostar, where the synchrotron emission is detected.

Radio observations suggest that the jets of IRAS 18162−2048 are precessing, because the direction of them at $z_{\rm p}$ is different than the direction where the HH objects are located. We assume that now the head of the jet is at $z_{\rm p}$, and HH80-81 and HH80 N are old ejections, $\sim$ 4000 yr before. The head of the jet moving through the molecular cloud forms two shocks: a reverse shock in the jet, and a bow shock in the cloud, with velocities $v_{\rm rs}|_{\rm bs} = v_{\rm j} - 3v_{\rm bs}/4$ and $v_{\rm bs} = v_{\rm j}/(1+\sqrt{1/\chi})$, respectively, where $\chi \equiv n_{\rm j}/n_{\rm mc}$ and $n_{\rm j}$ and $n_{\rm mc}$ are the densities of the jet and the molecular cloud, respectively. At $z_{\rm p}$ the width of the jet is $R_{\rm j} \sim 10^{17}$ cm, given $n_{\rm j} = \dot{M}/(\pi R_{\rm j}^2 v_{\rm j}) \sim 2.6\times10^2$ cm^{-3}, where $\dot{M} \sim 10^{-5}$ M$_\odot$ yr^{-1} [3]. At the location of HH80-N $n_{\rm mc}(z\sim 2.5\,{\rm pc}) \sim 400$ cm^{-3} [4] is deduced from H_α luminosity, and using that $n_{\rm mc} \propto z^{-1.5}$ [5] we obtain that at 0.5 pc $n_{\rm mc} \sim 3\times10^3$ cm^{-3}. Thus we obtain that $\chi(z_{\rm p}) \sim 0.02$ giving an adiabatic reverse shock with velocity $v_{\rm rs} \sim v_{\rm j}$ and a radiative bow-shock.

PARTICLE ACCELERATION AND NON-THERMAL EMISSION

Being that adiabatic shocks are propitious to accelerate particles via the Fermi-I mechanism, we assume that the electrons (e) that emit the detected synchrotron radiation at $z_{\rm p}$ are accelerated in the jet reverse shock (located also at $z_{\rm p}$). Even though there is no observational evidence of the presence of relativistic protons (p) in the jet of IRAS 18162-2048, these particles can be accelerated via Fermi-I as well as electrons, and we will take into account a population of non-thermal protons in our calculations. Particles accelerated in the reverse shock are injected in the downstream region following a power-law energy distribution $Q_{e,p} \propto E_{e,p}^{-2}$. The injection function Q is modified by radiative and escape losses in such a way that the part of the electron spectrum N_e that produces the synchrotron emission between 1.5 and 15 GHz is $N_e \propto E_e^{-2}$. Considering equipartition between the magnetic and the relativistic particle energy densities, i.e. $B^2/(8\pi) = U_e + U_p$, and the synchrotron fluxes given in [2], the magnetic field at $z_{\rm p}$ results $B \sim 0.1$ mG [1].

Electrons lose energy via synchrotron, Inverse Compton (IC) scattering and relativistic Bremmstrahlung, but escape losses via downstream matter advection is more efficient, with a timescale $t_{\rm adv} \sim 4R_{\rm j}/v_{\rm j} \sim 4\times10^9 (v_{\rm j}/(1000\,{\rm km\,s^{-1}}))^{-1}$ s as is shown in Figure 1 (left). Relativistic Bremsstrahlung losses have a timescale $t_{\rm Brem} \sim 1.4\times 10^{11}(n_{\rm j}/260\,{\rm cm^{-3}})^{-1}$ s, being this process the most efficient leptonic radiative channel at high energies. IC losses are not relevant because at $z_{\rm p}$ the energy density of stellar photons is low: $U_{\rm ph} \sim L_\star/(\pi z_{\rm p}^2 c) \sim 9.4\times10^{-11}$ erg s^{-1}. Relativistic protons radiate through proton-proton (pp) collisions on a timescale $t_{\rm pp} \sim 1.9\times10^{11}(n_{\rm j}/260\,{\rm cm^{-3}})^{-1}$ s. Advection losses constrain the maximum energy of electrons and protons given $E_{e,\rm max} = E_{p,\rm max} \sim 2.8$ TeV, and $N_{e,p} \sim Q_{e,p}\,t_{\rm adv}$.

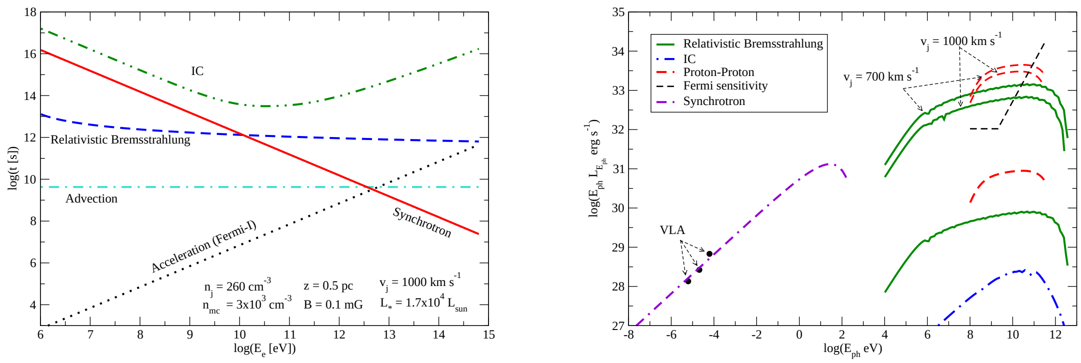

FIGURE 1. *Left*: Acceleration, escape, and electron cooling timescales. The parameters of the jet and the molecular cloud used are specified in the plot. *Right*: Spectral energy distribution. Relativistic Bremsstrahlung and pp collisions are computed considering the shocked density of the jet ($4n_{\rm j} = 1.1 \times 10^3$ cm^{-3}), and also the shocked density of the molecular cloud ($n_{\rm smc} = 9 \times 10^5$ and 1.8×10^6 cm^{-3}, for $v_{\rm j} = 700$, and 1000 km s^{-1}, respectively).

Gamma-ray emission

Knowing N_e and N_p we compute the spectral energy distribution considering the radiative processes mentioned in the previous Section (see Fig 1-right). We consider auto-absorption in the synchrotron spectrum and photon-photon attenuation at high energies, however this latter absorption process is not relevant at ~ 0.5 pc from the protostar. Considering two different values of $v_{\rm j}$: 700 and 1000 km s^{-1}, and the jet shocked density as target of relativistic Bremsstrahlung, and pp, the achieved bolometric luminosities of synchrotron radiation, IC scattering, relativistic Bremsstrahlung, and pp collisions result $L_{\rm sync} \sim 5 \times 10^{31}$, $L_{\rm ic} \sim 2 \times 10^{29}$, $L_{\rm Brem} \sim 8 \times 10^{30}$, and $L_{\rm pp} \sim 5 \times 10^{31}$ erg s^{-1}, respectively. We note that in this case $v_{\rm j}$ only affect the values of $E_{e,\rm max}$ and $E_{p,\rm max}$, given very similar bolometric luminosities.

We have mentioned that the most important cooling channels for electrons and protons are relativistic Bremsstrahlung and pp collisions, respectively. However, specific luminosities not larger than $\sim 10^{30}$ erg s^{-1} (relativistic Bremsstrahlung) and 10^{31} erg s^{-1} (pp) are achieved in the GeV domain by these radiation mechanisms. In order to produce a large amount of γ-rays, an increment in the density of target particles is needed. This can occur if we consider that, being the large densitiy contrast between $n_{\rm j}$ and matter downstream the bow shock, both materials can be mixed by Rayleigh-Taylor (RT) instabilities.

The radiative bow shock in the molecular cloud compresses the matter up to a density $n_{\rm smc} \sim 10^5 (n_{\rm mc}/10^3\,{\rm cm}^{-3})(v_{\rm bs}/100\,{\rm km\ s}^{-1})^2$ cm^{-3} after cooling via thermal emission up to reach a temperature of 10^4 K. Thus, being the large density contrast between $4n_{\rm j} \sim 10^4$ cm^{-3} and $n_{\rm smc}$, RT instabilities grow up to a wavelength $1/R_{\rm j}$ on a timescale $t_{\rm RT} \sim 0.1 t_{\rm j}$, where $t_{\rm j} \sim z_{\rm p}/v_{\rm j}$ [6,7]. Thus, at $z_{\rm p}$ the emitter (i.e. the reverse-shock downstream region) will be denser than $4n_{\rm j}$, and reaching a maximum value of $n_{\rm smc}$. Considering the maximum increase in the density of the emitter, i.e. efficient RT mixing, detectable values of γ-rays in the GeV domain are achieved, with specific relativistic Bremsstrahlung and pp luminosities larger than $\sim 5 \times 10^{32}$ and 5×10^{33} erg s^{-1}, respectively, as is shown in Fig 1 (right). However, note that detectable emission is achieved even in the case of less efficient mixing. By increasing the density of the emitter ~ 10 is enough to obtain detectable values of γ-rays.

CONCLUSIONS

The massive protostar IRAS 18162-2048 presents very collimated and powerful jets, and an accretion disc, characteristics that put this source as the prototype of a massive star formation system. In addition to that, the jet of IRAS 18162-2048 has a large velocity (~ 1000 km s^{-1}) and it is the unique protostellar jet with detection of polarized radio emission, mapping the direction of the magnetic field parallel to the jet velocity. The large value of $v_{\rm j}$ and the detection of polarization at radio wavelengths make the jets of IRAS 18162-2048 potential sources of γ-rays [6].

In the present contribution we model the non-thermal emission (from radio to γ-rays) produced at the location of the jet where synchrotron emission is clearly detected. Constraining the model with VLA data, and considering RT mixing between jet and molecular cloud shocked matter we obtain that the γ-ray emission produced in the north jet of IRAS 18162-2048 can be detected by the *Fermi* satellite in the GeV domain. We note that besides IRAS 18162-2048, there are other massive protostars that can be also γ-ray sources, as the case of IRAS 16547-4247 [8]. If high energy radiation from massive protostellar jets is detected, γ-ray astronomy can be used to shed light on the star forming process, and cosmic ray acceleration inside molecular clouds.

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