Mem. S.A.It. Vol. 81, 181

Memorie della

Gamma-ray emission from star-forming regions

Gustavo E. Romero[1,2]

[1] Instituto Argentino de Radioastronomía (CCT La Plata, CONICET), C.C.5, 1894 Villa Elisa, Buenos Aires, Argentina
[2] Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque, B1900FWA La Plata, Argentina, e-mail: romero@fcaglp.unlp.edu.ar

Abstract. Star-forming regions have been tentatively associated with gamma-ray sources since the early days of the COS B satellite. After the many sources detected by the Compton Gamma-Ray Observatory, the statistical evidence for such an association has became overwhelming. Recent results from imaging atmospheric Cherenkov telescopes indicate that some high-energy sources are produced in regions of active star formation like Cygnus OB2 and Westerlund 2. In this paper I will review what kind of stellar objects can produce gamma-ray emission in star-forming regions and I will suggest that the formation process of massive stars could in principle result in the production of observable gamma ray emission. Gamma-ray astronomy, will be argued, is mature enough as to contribute to the study of the birth of massive stars.

Key words. Gamma-rays – Associations of stars (OB) – Open clusters – Star formation

1. Introduction

The identification of star-forming regions (SFRs) with gamma-ray sources has a rather long story that can be traced till the first attempts to make statistical correlation analysis between COS-B data on high-confidence gamma-ray sources and SFRs (Montmerle 2000). With the advent of the Compton Gamma-Ray Observatory and the Energetic Gamma-Ray Experiment Telescope (EGRET) the statistical evidence for a physical association became overwhelming (Kaaret & Cottam 1996; Romero et al. 2000). In the early 1980s, theories of cosmic-ray acceleration in the strong winds of early-type stars were worked out in great detail and massive stars were proposed as potential gamma-ray sources (Cassé & Paul 2000; Völk & Forman 2000; White 2000; Pollock 2000). However, other types of sources could contribute to the gamma-ray emission detected in the direction of SFRs; sources such as accreting black holes, pulsars, supernova remnants, and pulsar wind nebulae. It was not until the discovery of the extended unidentified source TeV J2032+4130 in Cygnus OB2 by the HEGRA array of imaging Cherenkov telescopes in 2002 (Aharonian et al. 2000) that the hypothesis of a high-energy source powered by stellar effects in a SFR was considered sound from an observational point of view, despite early predictions (Giovannelli 2000). Since then, other two high-energy sources have been detected in SFRs: Westerlund 2 (Aharonian et al. 2000) and W43 (H.E.S.S. report at th 2008 Heidelberg meeting). All this points out in the

Send offprint requests to: G.E. Romero direction that early-type stars and the collective effects of their winds can accelerate particles beyond TeV energies and produce significant gamma-ray emission. In this review, I will discuss how gamma rays can be produced by stars in the different evolutionary stages of a SFR.

2. Massive star formation

The formation and early evolution of massive stars are not yet well understood. Two different basic mechanisms have been proposed. These mechanisms do not necessarily exclude each other. They are the accretion (Osorio et al. 2000; McKee & Tan 2000) and the coalescence (Bonnell et al. 2000) massive star formation processes. In the first case the massive star is formed by accretion of gas in a dense molecular core. Such an accretion episode is always accompanied by ejection of thermal jets that propagate inside the molecular cloud and sometimes even break out from it (Garay & Lizano 2000). In the coalescence picture the high-mass stars are formed by merging of low and intermediate mass protostars in the dense cluster environment. In either case the formation takes place inside a dense and giant molecular cloud. The SFR, then, starts as a giant dark cloud that is soon heated and illuminated by the star formation that goes on in its interior. As time goes by, the massive stars are formed and their strong winds sweep the ambient material giving rise to a mature open cluster.

The dense molecular clouds that are the cradles of massive stars have relative small sizes (< 0.1 pc), high temperatures that make of them strong IR sources ($T > 100$ K), densities of the order of $\sim 10^7$ cm^{-3} or higher, and high luminosities in the range of $10^4 - 10^6\ L_\odot$. The conditions of the medium are surely not homogeneous, with a power-law density distribution $n \propto r^{-p}$, with p in the range between 1.3 and 1.8 (Garay 2000). The massive stars are formed under very high infall mass rates of the order of $10^{-3} - 10^{-2}\ M_\odot$ yr^{-1}. The whole formation process is rather rapid, with timescales of the order of a few kyr.

One way to test the different scenarios proposed for massive star formation is the detection of outflows related to the accretion process in massive protostars. As we will see, there are some prominent examples of such outflows.

3. Collective effects in regions of star formation

Once a massive stellar association is formed, the combined effects of the stellar winds are expected to result in particle acceleration up to relativistic energies (Bykov & Fleishman 2000; Giovannelli 2000; Bednarek 2000). In addition, supernova explosions of very massive (and hence quickly evolving) stars can help to create super-bubbles and collective shocks where particles can be efficiently accelerated. Hence, the average cosmic ray (CR) density in SFRs is expected to be higher than the galactic average. The locally generated CRs can interact with both extended passive targets, like molecular clouds, the rich intra-cluster medium (Black & Fazio 2000; Aharonian & Atoyan 2000; Gabici et al. 2000), or with the very same winds of the massive stars (Torres et al. 2000). In the latter case, a modulation effect due to convection is expected, and hence the low-energy emission would be greatly diminished or suppressed. Such a picture might correspond to that of extended TeV sources without significant correlated emission at low energies like TeV J2032+4130 (Butt et al. 2000,?; Horns et al. 2000).

4. Gamma-ray emission from massive stars and colliding wind binary systems

Individual hot stars with strong winds have been suggested also as potential sources of high-energy particles and gamma rays (Cassé & Paul 2000; Völk & Forman 2000; White 2000; Chen & White 2000; White & Chen 2000). In some of these works particle acceleration occurs mainly at the wind terminal shock and in others at shocks embedded in the winds. Some of these works predicted detections of isolated massive stars by EGRET, something that did not happen. Efficient electron and proton acceleration in the inner wind are unlikely, because of the strong losses to which both species are exposed during the processes. In addition, even if some gamma rays are produced they will be absorbed by the stellar photosphere producing electron-positron pairs.

Models based on colliding winds in massive binary systems, on the contrary, seem to be far more promising (Eichler & Usov 2000). The clear detection of non-thermal radio emission from the colliding wind region in some systems like WR140, WR146, WR 147, and Cyg OB2 #5 indicate that electrons are been accelerated up to relativistic energies in these binaries. These electrons are located relatively close to the secondary star, so they should have strong inverse Compton losses which might result in a detectable gamma-ray signal (Benaglia et al. 2000; Benaglia & Romero 2000). Protons can also be accelerated in the colliding wind shock and they can interact either with the wind material (Pittard & Dougherty 2000) or they can diffuse to interact with nearby molecular clouds (Benaglia et al. 2000). Detailed models have been recently developed for systems like WR140 (Pittard & Dougherty 2000; Reimer et al. 2000) and for WR20a (Bednarek 2000). This latter system, however, is not resolved at radio wavelengths and since it is very compact, strong high-energy photon absorption should take place. In addition, inverse Compton losses should impose a very low energy cutoff to the population of relativistic particles.

It is widely expected that GLAST-Fermi satellite and even perhaps AGILE could detect some colliding wind binaries as weak sources. Depending on the orbital parameters, these sources might appear as highly variable at MeV-GeV energies. It is however dubious whether they can accelerate particles up to TeV energies.

5. Gamma rays generated by massive protostars

In very young SFRs, the gravitational contraction of dense molecular cores can give rise to a very rich phenomenology. Molecular clouds are clumpy and highly inhomogeneous. In over-dense regions massive protostars are formed and ultra-compact regions of ionized gas surrounds them. The size of these regions is very small, ≤ 0.05 pc, implying short lifetimes of the order of 10^{3-4} yr. The cloud around the protostar is heated and radiates in the IR with extremely high luminosities that can reach 10^5 $L_\odot$ in some cases. The pre-stellar core is likely to have angular momentum resulting in the formation of protostellar disks. Evidence for the existence of such disks in been found through IR, optical and line observations. Magnetic fields, which are thought to be strong in the inner cores of the molecular clouds (Crutcher 2000), are dragged in and twisted by the infalling matter. The result is a magnetic tower that can launch and collimate a thermal jet, with terminal velocities of up to a few thousand km s^{-1}. Such outflows are observed in numerous clouds. The accretion rate at this phase can be as high as several times 10^{-3} $M_\odot$ yr^{-1}. The whole formation process can last $\sim 10^5$ yr.

As time goes by, the star starts to burn hydrogen and the subsequent wind blows up the circumstellar disk and the jet is quenched. Maser emission is a good tracer of the different aspects of the formation process. Three molecules are of particular importance: H_2O, OH, and CH_3OH. This maser emission not only acts as a signspot of active SFRs, but also provides unique information on the physical conditions in the inner regions of the molecular core.

Water maser emission is usually associated with the presence of molecular outflows and disks. The lines present a wide spread in velocities, that indicates the motions of the molecular material in the region. Hydroxyl masers are indicators of the presence of ultra-compact HII regions. They are always associated with the densest parts of the cloud, being originated in extremely small regions of less than 10^{16} cm. Finally, methanol lines arise in shocked gas that is located at the interface between the mass outflow and the external medium. Altogether, these maser lines can shed light on many aspects of the massive star forming process (Garay & Lizano 2000).

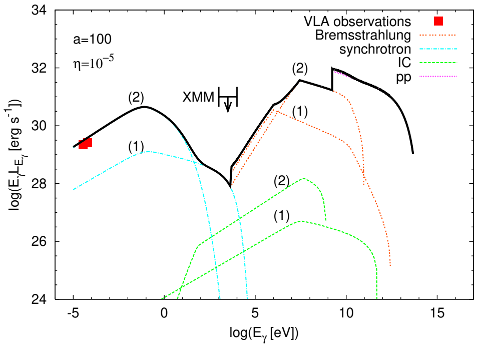

Fig. 1. Spectral energy distribution of the termination point of the jet of a massive young stellar object (Araudo et al. 2007).

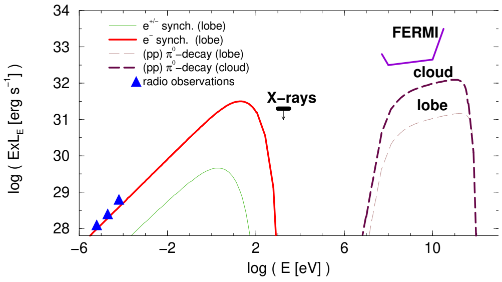

Fig. 2. Spectral energy distribution of particles accelerated in the reverse shock at termination point of the jet of a massive young stellar object. Diffusion into the molecular cloud and the corresponding *pp* contribution of the particles is considered in the total emission. The parameters correspond to HH 80-81. Fermi sensitivity at 5σ after 1 yr is indicated (Romero et al. 2009).

The jets of massive young stellar objects propagate through the molecular cloud and can break out from its boundaries or can end inside the cloud, remaining hidden at optical wavelength. Radio observations, however, reveal the presence of jets as thermal, elongated features (Martí et al. 2000). At the end points of the jets strong shocks are expected to form. These shocks can be sites of diffusive shock acceleration, as indicated by the detection of non-thermal emission of synchrotron origin in a few sources, like IRAS 16547−4247 (Garay et al. 2000; Rodríguez et al. 2000), Serpens, W3(OH) (Wilner et al. 2000) and HH 80-81 (Martí et al. 2000). The first case is particularly interesting, since it seems to be a massive protostar completely embedded in a dense molecular cloud with an extreme IR luminosity of $L \sim 6.2 \times 10^4 L_\odot \approx 2.4 \times 10^{38}$ erg s^{-1}. The source is located at 2.9 kpc (Garay et al. 2000). The total mass of the cloud is $M_{\rm cl} = 9 \times 10^2\ M_\odot$. Molecular line observations indicate that the size of the cloud is $\sim$ 0.38 pc in diameter ($\approx 1.1 \times 10^{18}$ cm). Assuming a spherical geometry, the averaged particle (atoms of H) density of the cloud is $n_{\rm cl} \approx 5.2 \times 10^5$ cm^{-3}. The energy density of IR photons in the cloud, assuming an homogeneous distribution, is $w_{\rm ph} \approx 1.8 \times 10^{-9}$ erg cm^{-3}.

The combined effect of many protostars in the core of a very young OB association might be even responsible for some unidentified EGRET sources found in the plane in positional coincidence with such associations (Romero et al. 2000). The higher angular resolution of GLAST can differentiate the different individual contributions after long exposures.

In the case that the jet has slowed down significantly, the most propitious site for particle acceleration will be the reverse shock in the thermal plasma of the outflow. Protons can escape and diffuse into the swept material and the molecular cloud. Such a situation is illustrated in Fig. 5, where we show a spectral energy distribution estimated for the case of the region HH80-81 (Romero et al. 2000).

Radio observations made with the Australia Telescope Compact Array and the deeper observations with the Very Large Array show the existence of a triple radio source inside the molecular cloud. The three components of the radio source are aligned in the northwest-southeast direction, with the outer lobes separated from the core by a projected distance of 0.14 pc. The central source is elongated and has a spectral index of 0.33 ± 0.05 ($S_\nu \propto \nu^\alpha$), consistent with free-free emission from a collimated jet (Rodríguez et al. 2000). The integrated emission from the northern lobe has a spectral index of −0.32 ± 0.29, of dubious thermal/non-thermal nature. The southern lobe, instead, is clearly non-thermal, with an index $\alpha = -0.59 \pm 0.15$. The inferred linear size for this lobe is $\approx 10^{16}$ cm.

The presence of relativistic particles in such a complex medium suggest that high-energy emission is likely to occur due to relativistic Bremsstrahlung and inverse Compton interaction with IR photons in th case of electrons, and through inelastic *pp* collisions in the case of nuclei. The magnetic field in the region of non-thermal radio emission can be estimated assuming equipartition and the obtained values are in agreement with direct measurements by Zeeman effect (Crutcher 2000). Typical fields are of the order of 10^3 G. The acceleration efficiency through diffusive shock acceleration at the terminal jet region in the jet material is small ($\sim 10^{-5}$) but enough to yield maximum energies for primary electrons and protons of the order of 3 TeV and 60 TeV, respectively, in the case of a proton to electron density ratio of 100, similar to what is observed in the galactic cosmic ray spectrum. The spectral energy distribution produced by these particles through the different cooling radiative mechanisms is shown in Fig. 5. In this spectrum not only the contribution from primary particles is shown, but also the emission from secondary pairs resulting from charged pion decay chains (Araudo et al. 2000).

6. Conclusions

Star-forming regions can generate gamma-rays through different processes during their evolution from dark clouds to open clusters. In the early stages of star formation, the contribution from individual protostars can reach integrated luminosities above 100 MeV of around 10^{33} erg s^{-1}. The composed emission of several of such YSO can illuminate the massive dark cloud in gamma-rays producing a detectable source. Higher resolution telescopes like LAT of the GLAST-Fermi satellite might resolve the individual sources, then opening a new observational window to the study of massive star formation. Strong IR luminosities, non-thermal radio emission and maser activity are the best tracers for such young protostellar objects.

Once the SFR has aged and early-type massive stars are formed, colliding wind binaries can be significant gamma-ray sources for GLAST-Fermi satellite. Luminosities up to 10^{34} erg s^{-1} at $E > 100$ MeV can be expected for WR-OB systems like WR 140. The best indication of efficient particle acceleration in such objects is the clear detection of no-thermal radio emission from the colliding wind region. Protons might escape the system illuminating nearby molecular clouds.

When the SFR has evolved into an open cluster, the collective effect of stellar winds of the strongest O stars and supernova remnants can produce large-scale effects, including particle acceleration up to TeV energies. Such heterogeneous sources can be detected in gamma rays with Cherenkov telescope arrays as extended sources positionally coincident with OB associations and open clusters.

Regarding isolated massive stars, it seems very dubious to the author whether they can produce a significant amount of high-energy emission. Particle acceleration in the inner stellar winds could hardly be efficient, and in any case losses, both radiative and adiabatic, make very difficult for the particles to reach high-energies.

Star-forming regions are promising sites for the production of gamma rays, by different mechanisms, along their entire evolution. In the next few month and years, star formation studies might incorporate gamma-ray astronomy to probe the most extreme consequences of the formation and evolution of massive stars.

7. DISCUSSION

WOLFGANG KUNDT : I appreciate your evidences of non-thermal emission by bi-polar flows in star forming regions, but I mistrust the boosting scenario which you propose: it is likely to violate the Second Law of Thermodynamics. My preferred model is pair-plasma jets created by the distortions of the YSO's magnetosphere (Ap&SS, 148, 343, 1988). See also my work with Gopal-Krishna in my homepage under 'hot topics' (URL: www.astro.uni-bonn.de/~wkundt/).

GUSTAVO E. ROMERO: Thanks for your comment and the references. In the case of YSO I must remark that molecular outflows are observed with sub-mm instruments, suggesting that the outflow is baryon-loaded.

Acknowledgements. I am grateful to Franco Giovannelli and Lola Sabau-Graziati for a delightful meeting. My work on high-energy astrophysics is partially supported by CONICET and ANPCyT through grant PICT-2007-00848, BID 1728/OC-AR. Additional funding comes from grant AYA 2007-68034-C03-01, FEDER funds.

References

Aharonian, F.A., and Atoyan, A.M., 1996, A&A, 309, 917
Aharonian, F.A., et al., 2002, A&A, 393, L37
Aharonian, F.A., et al., 2007, A&A, 467, 1075
Araudo, A.T., et al., 2007, A&A, 476, 1289
Bednarek, W., 2005, MNRAS, 363, L46
Bednarek, W., 2007, MNRAS, 382, 367
Benaglia, P., et al. , 2001, A&A, 366, 605
Benaglia, P., and Romero, G.E., 2003, A&A, 399, 1121
Benaglia, P., et al., 2005, A&A, 440, 743
Black, J., and Fazio, G.G., 1973, ApJ, 185, L7
Bonnell, I.A., Bate, M.R., and Zinnecker, H., 1998, MNRAS, 298, 93
Butt, Y.M., et al., 2003, ApJ, 597, 494
Butt, Y.M., et al., 2006, ApJ, 643, 238
Bykov, A.M., and Fleishman, G.D., 1992, MNRAS, 255, 269
Cassé, M. and Paul, J.A., 1980, ApJ, 237, 236
Crutcher, R.M., 1999, ApJ, 520, 706
Chen, W. and White, R.L., 1991, ApJ, 381, L63
Eichler, D., and Usov, V., 1993, ApJ, 237, 236
Gabici, S., Aharonian, F.A., and Blasi, P., 2007, Ap&SS, 309, 365
Garay, G. and S. Lizano, S., 1999, PASP, 111, 1049
Garay, G., et al., 2003, ApJ, 537, 739
Garay, G., 2006, RevMexAA (Serie de Conferencias), 26, 13
Giovannelli, F., 1996, MmSAI, 67, 289
Horns, D., et al., 2007, A&A, 469, L17
Kaaret, P., and Cottam, J., 1996, ApJ, 462, L35
Martí, J., Rodríguez, L.F., and Reipurth, B., 1995, ApJ, 449, 184
McKee, C.F., and Tan, J.C., 2003, ApJ, 585, 850
Montmerle, T., 1979, ApJ, 231, 95
Osorio, M., Lizano, S., and D'Alessio, P., 1999, ApJ, 525, 808
Pittard, J.M. and Dougherty, S.M., 2006, MNRAS, 372, 801
Pollock, A.M.T., 1987, A&A, 171, 135
Reimer, A., Phol, M., and Reimer, O., 2006, ApJ, 644, 1118
Rodríguez, L.F., et al., 2005, ApJ, 626, 953
Romero, G.E., Benaglia, P., and Torres, D.F., 1999, A&A, 348, 868
Romero, G.E., et al., 2009, in preparation
Torres, D.F., Domingo-Santamaría, E., and Romero, G.E., 2004, ApJ, 601, L75
Völk, H.J., and Forman, M., 1982, ApJ, 253, 188
White, R.L., 1985, ApJ, 289, 698
White, R.L., and Chen, W., 1992, ApJ, 387, L81
Wilner, D.J., Reid, M.J., and Menten, K.M., 1999, ApJ, 513, 775