Cosmic rays and star forming regions in our Galaxy

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on behalf of S. Molinari & Herschel Hi-GAL Team
One key problem to understand in the field of star formation is the origin of the low star-formation efficiency (SFE) observed in our Galaxy.

The SFE can be estimated through the ratio $M_*/M_\text{g}$ where $M_*$ is the mass of the formed (or forming) stars, while $M_\text{g}$ is the total mass of the available gas.

Typical values for SFR are few %; with Herschel data from the Hi-GAL program, Elia et al. (2013) find SFE < 1% in the outer Galaxy.

Two mechanisms proposed to explain such a low values:

- Magnetic field: requires an agent (eg CR) to ionize the ISM
- Turbulence
Cosmic Rays are the sole source of ionization in the dense and heavily extincted molecular clouds.

Establishing a link between CR and star formation would answer two completely different questions: are the $\gamma$-rays produced in a hadronic scenario? Is the magnetic field dominant in keeping the SFE low?
Gravity & Magnetic field

- During contraction, matter can slide freely along field lines. Ionized gas moving in the orthogonal direction tugs on the field and is retarded by thermal pressure, as well as by magnetic tension (function of the plasma density) that opposes self-gravity.
- Neutrals drift w.r.t. the plasma with a frictional force \( F_{ni} = m_{ni} n_i n_i <\sigma v_{rel}> (v_i - v_n) \), that also depends on the ISM ionization fraction.
- The net result is a loss of magnetic flux, after which the cloud can now contract more easily.
This process is called **ambipolar diffusion**

It depends on the **ionization fraction of the ISM** and solves the problem of how stars form in the presence of a magnetic field.

It is also invoked as a **self-regulating mechanism of star formation**: the more stars are formed the higher the UV flux is → higher ionization fraction.
Numerical simulations of star formation in cluster show that the efficiency and rate of the process strongly depend on the intensity of the magnetic field.

The efficiency of B in opposing collapse is higher the higher is the ionization fraction in the early stages of star formation.

Price & Bate 2009
Steady-state bath of Cosmic Rays

- Quantify the importance of magnetic field in star formation
- Estimate an initial ionization fraction in the star-forming region
- Derive the Star Formation Rate
- Understand if and how a normal Galaxy self-regulates its star formation behaviour
Herschel

- Orbit around L2
- Launched: May 14\textsuperscript{th} 2009
- End of Helium: April 29\textsuperscript{th} 2013
- Loss of contact: June 13\textsuperscript{th} 2013
Hi-Gal
A Herschel Key-Project to map the Galactic Plane in the Far-IR

Simultaneous 5-bands (70-160-250-350-500μm) continuum mapping of 720 sq. deg. of the Galactic Plane (|b| ≤1°)

With almost 900 hours observing time is the largest OPEN TIME Herschel KP

Galaxy-wide Census, Luminosity, Mass and SED of dust structures at all scales from massive YSOs to Spiral Arms
The AGILE gamma-ray sky (E > 100 MeV)  
2 year exposure: July 2007 - June 2009
Three years of LAT scanning data (E > 1 GeV)
Toward a Predictive Global Model of Galactic Star Formation

Hi-GAL Team & ESA

Hi-GAL
Herschel infrared Galactic Plane Survey

Herschel 70-160-350\(\mu\)m composite

The Hi-GAL Team Institutes [PI: S. Molinari, INAF-IAPS Rome]


Hi-GAL data processing is carried out at INAF-IAPS (Rome) thanks to support from Agenzia Spaziale Italiana under Contract I/038/08/0
Column density map from Herschel/Hi-GAL

Automatic Filament Extraction: Schisano et al. 2013
The Galactic Web of Star Formation

Molinari+ 10
Dense filaments are the critical incubators for Star Formation. They are an unexpected discovery of HERSCHEL, and the next Hot Topic in Galactic Star Formation.

Evolutionary effects are clearly visible as a function of the filaments linear masses.
Do more massive clumps form on more massive filaments? Or do filaments grow mass from the surrounding environments and channel more mass to the clumps? We do not know!
H-R diagram analogues. L/M: Evolution?

- A separation between pre-stellar and proto-stellar sources is quite clear in terms of L/M. The appearance and intensity of the 70µm (and shortward), clearly makes the difference.
- Within each class, there is a clear trend of L/M with Temperature (estimated using only $\lambda \geq 160\mu m$).

Star Formation drives up the energy budget in the clump, raising its global temperature and luminosity. This can be ideally followed in the [L,M] diagram.
Star Formation Rate from YSO counts

A first attempt in deriving the SFR in the two Hi-GAL SDP fields $l=30^\circ$ and $l=59^\circ$ (Veneziani et al. 2012), comparing YSO statistics in the $L \ vs \ M$ plot against evolutionary predictions

$$SFR = \sum_{i=1}^{N_{\text{Sources}}} \sum_{j=1}^{N_{\text{Mzams}}} n_M(i,j) M_{\text{ZAMS}}(i) / t_f(i)$$

Each bin $i$ will be associated to:
- final ZAMS mass $M_{\text{ZAMS}}(i)$
- formation time $t_f(i)$

$l=30^\circ \sim 0.067 \ M_{\text{sun}} \ / \ yr$

$l=59^\circ \sim 0.011 \ M_{\text{sun}} \ / \ yr$
For the first time it will be possible to obtain a spatially resolved map of the Star Formation Rate and Efficiency in the Milky Way. The results on the outer Galaxy are being produced.
near η Carinae
The Cygnus Region
W44 (Giuliani et al. 2011)
Ecco la zona più interna della nostra Galassia rivelata da AGILE ad altissima risoluzione (400 MeV-1 GeV). La regione ospita al centro un buco nero di circa 4 milioni di masse solari (indicato dall’asterisco) che però non appare emettere radiazione gamma significativa.
The Galactic Center with Herschel
The 5 Hi-GAL maps were cross-calibrated to Planck and IRAS (e.g Bernard et al. 2010) and rebinned at the resolution of the 350µm (≈25″).

Pixel-to-pixel SEDs were fit with DustEM (Compiegne et al. 2010) with opacities $\tau_{250}/N_H = 8.8 \times 10^{-26} \text{ cm}^2/\text{H}$, to obtain Temperature and Column Density.
Conclusions

• There are very promising and largely unexplored synergies between $\gamma$-ray and infrared astronomy in the field of Star Formation

• We are starting now with the AGILE Group the work of correlating the results from Hi-GAL with the diffuse $\gamma$-ray maps of AGILE and Fermi; this will be one of the tasks for our recently approved FP7-SPACE project, called VIALACTEA

but….

more resolution in the $\gamma$-ray…..please.