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Global star formation in the Milky Way with Hi-GAL, the Herschel infrared Galactic Plane Survey

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Abstract. Dust is a most important and effective tracer of the global structural, physical and evolutionary conditions of the ISM material throughout the whole life-cycle of a galaxy. From diffuse interstellar cirrus to dense molecular clouds, from protostars to post-AGB envelopes, from supershells to supernovae remnants, the equatorial plane of our Galaxy provides the ideal laboratory to carry out investigations of the global and integrated properties of the different phases of the Galactic ISM, their evolution and interactions.
Hi-GAL is the *Herschel* Open Time Key-Project that will map 240 square degrees of our Inner Galaxy, delivering the ultimate census, temperature, luminosity, mass and Spectral Energy Distribution of star forming regions and cold ISM structures in all the environments of the Galactic ecosystem, at unprecedented resolutions, and at all scales from massive objects in protoclusters to the full spiral arm.
Hi-GAL will enable decisive steps toward the formulation of a global predictive model of the ISM/star formation cyclic transformation process which is the engine responsible for most of the energy budget in normal star-forming galaxies. It will be a cornerstone to unveil the evolution of galaxies through redshift back to their formation.

Key words. Stars: formation – (*ISM*:) dust – Galaxy: evolution – Galaxy: structure – Infrared: ISM – Submillimeter – Surveys

1. Introduction

Dust is the most robust tracer for the ‘Galactic ecology’ - the cycling of material from dying stars to the ionized, atomic, and molecular phases of the InterStellar medium (ISM), into star forming cloud cores, and back into stars. Atoms, ions, and molecules are imperfect tracers because they undergo complex phase changes, chemical processing, depletions onto grains, and are subject to complex excitation conditions. In contrast, dust is stable in most phases of the ISM; it is optically thin in the Far Infrared (FIR) over most of the Milky Way Galaxy, so that its emission and absorption simply depend on emissivity, column density and temperature. Cold dust in particular (10K≤T≤ 40K) traces the bulk of non-stellar baryonic mass in all the ”habitats” of the Galactic ecosystem, for the 60-600μm spectral range covered by the PACS and SPIRE cameras on board the *Herschel* satellite is ideally suited.

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Hi-GAL will map the inner Galactic Plane (-60°≤ l ≤ +60°, -1°≤ b ≤ +1°) in 5 photometric bands between 60 and 600μm at a 4-40″ diffraction limited spatial resolution. Hi-GAL embodies the optimum combination of *Herschel* wavelength coverage, sensitivity, mapping strategy and speed to deliver, in a single and homogeneous dataset of extraordinary legacy value, the ultimate census, temperature, luminosity, mass and Spectral Energy Distribution of star forming regions and cold ISM structures in all the environments of the Galactic ecosystem, at unprecedented resolutions, and at all scales from massive objects in protoclusters to the full spiral arm. The legacy of mid to far infrared (FIR) surveys of the Galactic Plane is indeed rich in scientific discovery. Unbiased surveys make possible dramatic leaps in our understanding because they provide homogeneous data for a large number of objects allowing firm statistical inferences about global properties. Systematically executed, large surveys such as IRAS (Neugebauer et al. 1984), MSX (Price et al. 2001), GLIMPSE (Benjamin et al. 2003) and MIPSGAL (Carey et al. 2005) dramatically changed, and are still shaping, our understanding of the Galactic ecosystem.

The Hi-GAL team is a world-wide consortium of Institutes and Universities from Italy (IFSI, Oss. Arcetri, Univ. of Rome, Univ. of Lecce), United States (IPAC-Caltech, JPL, Univ. of Colorado, Harvard-CfA), France (CESR, IAS, Cea/Saclay, OAMP), United Kingdom (RAL, Univ. of Cardiff, UCL, John Moores Univ., Univ. of Hertsfordshire, Univ. of Leeds), Canada (Univ. of Toronto, Univ. of Calgary).

2. Star formation life-cycle in the Milky Way

While the majority of the survey scientific potential will be for the general community to exploit, our consortium will mainly concentrate on understanding how the formation of stars, and massive stars in particular, shapes the evolution of the Galaxy. Massive stars are responsible for the global ionization of the Interstellar Medium (ISM). Their energetic stellar winds and supernova blast waves direct the dynamical evolution of the ISM, shaping its morphology, energetics and chemistry, and influencing the formation of subsequent generations of stars and planetary systems. Star formation drives the evolution of ordinary matter in the Universe from its primordial composition to the present-day chemical diversity necessary for the birth of life. Despite their importance, remarkably little is known about how massive stars form (McKee & Tan 2003). The lack of a fundamental theory of star formation or, rather, of a galaxy-scale predictive model for star formation, is the key issue which is perceived as a major hurdle to the understanding of galaxy formation (Silk 2003). Significant advances in this field require that the following issues are addressed: *i*) What is the temperature and structure of the ISM? *ii*) How do molecular clouds form? *iii*) What is the relationship of the stellar initial mass function (IMF) to the mass function (MF) of ISM structures and cloud cores on all scales? *iv*) How do massive stars and clusters form? *v*) How does the Star Formation Rate (SFR) and Efficiency (SFE) vary as a function of Galactocentric distance and environmental conditions such as the intensity of the Interstellar Radiation Field (ISRF), ISM metallicity, proximity to spiral arms or the molecular ring, external triggers, and total pressure? *vi*) Do star formation thresholds exist in our Galaxy, where are they, and what governs their location? *vii*) How do the local properties of the ISM and the rates of spontaneous or triggered star formation relate to the global scaling laws observed in external galaxies?

The rest of this contribution will briefly outline how the data provided by the Hi-GAL survey will uniquely contribute to answering these questions.

2.1. The ISM temperature structure

Far-IR emission is produced by large dust grains which dominate the total dust mass and trace all phases of the ISM. Variations of the FIR emissivity (FIR emission over column density ratio) are dominated by the non-linear effect of dust temperature through the Planck function. Fortunately, the shape of the SED as measured by PACS and SPIRE will be most sensitive to temperature variations as the spectral bands sample the peak of the Big Grain emission and the contribution of Very Small Grains can be estimated from the Hi-GAL data at 70μm and MIPSGAL at 24μm. The dust temperature (T_d) and its spatial variations will therefore be measured precisely. This important parameter is directly related to the InterStellar Radiation Field (ISRF) strength and spectral shape, which is set by the present stellar content in a given region. So far, the dust temperature along the Galactic Plane has only been mapped at a resolution of 40′ (Lagache et al. 1998) using DIRBE. Hi-GAL will improve this by a factor of about 100 in linear scales. It will trace the local radiation field on scales relevant to star formation, and provide mass estimates even at large distances.

With temperature-induced variations constrained, residual fluctuations of the FIR emissivity can be traced by comparison with the HI, CO, Hα, γ-ray surveys and interpreted as dust abundance, size distribution or optical properties variations. Abundance variations will be studied using galactic inversion techniques (Paladini et al. 2007) which allow detection of significant abundance variations throughout the MW, presumably due to the metallicity gradient related to past and present star formation activity but have been till now limited by poor angular resolution and uncertainties in the temperature measurements. Size distribution effect should be small in most cases, and can be evidenced through detailed model fitting of the SED. Variations in the dust optical properties may also occur independent of metallicity, e.g. from dust coagulation in dense regions or low level transitions in amorphous solids (Meny et al. 2007).

2.2. The formation of molecular clouds

About half of the mass in the ISM is in molecular clouds (MCs); most of that material resides in giant molecular clouds (GMCs). How do GMCs form and evolve until the onset of star formation, which eventually disrupts them?

In the traditional *"slow formation"* picture, distributed material is accumulated by large-scale perturbations such as the passage of a spiral arm. Shielding by dust and surface reactions on grains promotes the HI→H_2 transition, which in turn allows the formation of other molecules that cool the cloud. Gravity, mediated by the magnetic fields leads to star formation. In this scenario cloud lifetimes are about ~30 Myr (Leisawitz et al. 1989). This picture has difficulty explaining the absence of quiescent, non star forming GMCs (however, see Palla & Galli 1997) and the continuous re-generation of turbulence needed to support GMCs for many crossing times.

An alternative, *"fast formation"* scenario has been proposed (Hartmann et al. 2001) in which most MCs are transient, short-lived structures (Padoan & Nordlund 2002) created in the post-shock regions of converging large-scale flows and stars form on very short timescales (Elmegreen 2000). However, rapid MC formation requires rapid HI→H_2 conversion (Goldsmith & Li 2005) which in turn requires either high-density pre-shock conditions (n~200 cm^{-3}, T≤100K; (Pringle et al. 2001), or strong turbulence (Glover & Mac Low 2007), higher than observed.

Direct detection of cold (i.e. T<20 K) dust, possibly the quiescent counterparts to traditional molecular clouds, has been difficult (Sodroski et al. 1994; Lagache et al. 1998) either because of insufficient wavelength coverage (e.g. IRAS) or inadequate spatial resolution (DIRBE, FIRAS). CO observations are problematic due to molecular freeze-out onto grains (Flower et al. 2005), or photochemical effects in low-metallicity environments (Bot et al. 2007). The recent detection of very cold clumps in the Galactic Plane with Archeops (Désert et al. 2008) however, confirms the FIR and submm continuum as the best tool to *directly* trace cold ISM components. Notable examples are Infrared Dark Clouds (IRDCs) and HI Self-Absorption (HISA) clouds.

With the Hi-GAL survey we will detect and characterize cold structures in the Galactic Plane and classify them based on star formation activity. Detection statistics for clouds with different temperatures and degree of star formation activity will provide the fraction of quiescent *vs* star-forming clouds, allowing us to attack the slow/fast issue from firm statistical grounds. Variations with Galactocentric radius will determine if the *slow/fast* scenarios are mutually exclusive or reflect different initial/environmental conditions.

2.3. The timeline for the formation of massive stars

The paradigm for the formation of solar-type stars via accretion through a circumstellar disk (Shu et al. 1987) predicts an evolution from cores to protostars, and finally pre-main sequence stars that is well matched with distinctive characteristics of their SED (Lada & Wilking 1984; Andre et al. 1993).

Application of a SED-based classification tool to a large sample of luminous protostar candidates in the Galactic Plane will define a timeline for the various phases of massive star formation that will constrain the theories and lead to new estimates of the SFR.

An evolutionary sequence (cold massive cloud core; Hot Molecular Core (HMC)+outflow; IR-bright massive YSOs; ultracompact (UC) HII region) has been proposed (e.g. Evans et al. 2002), but it is qualitative and based on small samples. Samples of bright and massive YSOs (Molinari et al. 1996; Sridharan et al. 2002; Hoare et al. 2004) are IRAS or MSX selected and tend to suffer from age biases and confusion which prevent firm quantitative conclusions. A phase of intense, accelerating accretion prior to H-burning ignition may be observable (e.g. Molinari et al. 1998) in the form of dense condensations devoid of IR as well as radio continuum emission, seems confirmed by recent large mm surveys (Beltrán et al. 2006; Hill et al. 2005). Millimeter continuum alone, however, cannot distinguish between pre-collapse condensations and rapidly accreting cores; Hi-GAL will use the full potential of Herschel wavelength coverage and spatial resolution to trace the SED peak of dust envelopes in all phases from massive pre-stellar condensations to UCHII regions.

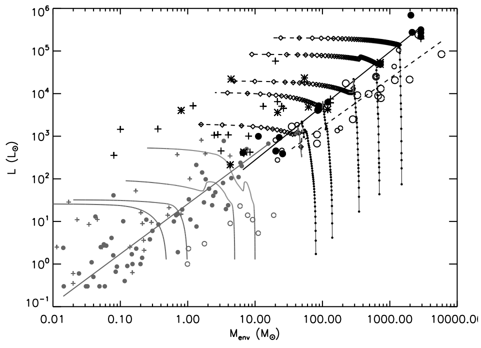

Fig. 1. L_{bol} *vs* M_{env} diagram illustrating the evolution of Young Stellar Objects of different masses from accretion to (and through) the ZAMS. Symbols identify different classes of observed objects; dotted lines represent model evolutionary tracks (from Molinari et al. 2008).

Herschel will accurately measure the bolometric luminosity of massive YSOs; this quantity rises by several factors in few 10^4 years during accretion, boosting the potential of L_{bol}-M_{env} diagnostic (Fig. 1) as a powerful evolutionary tool (Molinari et al. 2008). These investigations will be possible up to several Kpc.

The abundance of high mass YSOs per mass bin in the various evolutionary phases will provide the duration of each phase. This timeline can be directly compared with the prediction of various models, and together with the YSO mass function, will be used to infer the SFR. Using standard assumptions for the IMF and the SFR, we expect to detect several thousands objects in different evolutionary phases, providing statistical significance to identify trends due to variations with Galactocentric radius, proximity to existing OB associations and spiral arms.

2.4. Bridging the gap between local and global star formation

Large-scale cosmological simulations (e.g. Springel et al. 2005) predict the formation of structure on the scales of galaxies and clusters of galaxies. Stellar population synthesis models follow the evolution of galaxies, once the stars are in place. But the missing link is an understanding of large-scale star formation, involving high-mass stars, star clusters, and feedback, and a determination of how the SFE and IMF depend on that feedback, especially with current models requiring a top-heavy IMF in starbursts (Lacey et al. 2008). Considerable effort in this respect has been focused on analyzing the integrated properties of galaxies. The global SFE, and SFR are all critical figures of merit against which model predictions are verified and are commonly used to seek scaling-laws and statistical trends to unveil the roles of various agents in a galaxy's evolution. Progress is not straightforward. For example, while the FIR/radio correlation suggests that the SFR ($\geq$5 $MM_\odot$/yr) is the dominant variable controlling the FIR and radio luminosities in galaxies (Condon 1992), phenomenological parameterization of the SFR against, e.g., global FIR SED (Dale et al. 2001), provides limited physical insight into the underlying star-forming agents. Likewise, the global "Schmidt" law relating the SFR and ISM density (Schmidt 1959), and the existence of star-formation thresholds in external galaxies, cannot relate the onset of star formation unequivocally to global gravitational instabilities (Kennicutt 1989) vs a combination of external triggers (Elmegreen 2002).

Hi-GAL will enable quantitative analysis based on basic observables - the luminosity functions of YSOs, the mass function of dense star-forming structures and quiescent clouds. Hi-GAL will provide the essential context of high-mass star formation, relative to molecular gas, HI gas, stars, HII regions, OB associations, SNRs and spiral arms. Theoretical models and numerical simulations will be tested in multiple ways. We will discover whether a local triggering agent is necessary for high-mass star formation or if a spiral arm is sufficient, clarifying the differences between spontaneous and triggered star formation. We will quantify the relationship between the interaction strength (estimated using available data from ancillary surveys) and the resulting increase in SFE above the spontaneous rate. By locally relating the SFR to the properties of the ISM we will probe star formation thresholds as a function of environment and spatial scale, and possibly unveil the mechanism giving rise to global Schmidt-like scaling laws. We will determine the dominant physical process underlying triggering.

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