Star Formation in the Milky Way. The Infrared View.

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Abstract I present a brief review of some of the most recent and active topics of star formation process in the Milky Way using mid and far infrared observations, and motivated by the research being carried out by our science group using the data gathered by the Spitzer and Herschel space telescopes. These topics include bringing together the scaling relationships found in extragalactic systems with that of the local nearby molecular clouds, the synthetic modeling of the Milky Way and estimates of its star formation rate.

1 Introduction

In December 2007 we, Kartik Seth and I, organized a meeting in Pasadena called “The Evolving ISM in the Milky Way and Nearby Galaxies” (Seth, Noriega-Crespo, Ingalls & Paladini [26]); it was the fourth conference under the auspices of the Spitzer Science Center. The main goal of that meeting was to bring together two communities using the same tools, methodology and looking essentially at the same issues, with the only differences being on the spatial scales and samples of astrophysical objects that they were studying. Two of the leading participants were Dr. Neal Evans and Dr. Robert Kennicutt, both Principal Investigators of two very successful Spitzer Legacy Surveys, “c2d” ('Core to Disks') and “SINGS” ('The Spitzer Infrared Nearby Galaxies Survey'), respectively. Both interested on the star formation process, one locally (Evans) and one on nearby galaxies (Kennicutt). Therefore, it was not a surprise that the same day I gave this presentation at Sant Cugat in the workshop on Cosmic-ray induced phenomenology in star-forming environments, that Kennicutt and Evans submitted to astroph [14] a review on “Star Formation in the Milky Way and Nearby Galaxies” to appear in the Annual Reviews of Astronomy and Astrophysics during the Fall of 2012 [14]. And although their review is
certainly more ambitious and complete than this summary, I was quite pleased to see that we identified some of the same main issues and progress on the subject.

Understanding the star formation process locally or in extragalactic systems is a very active research area, and where infrared observations have played a major role in bringing together a wholistic view. Measuring the star formation rate (SFR) of the Milky Way (MW) or other galaxies is like “taking their pulse” (Chomiuk & Povich [7]), since the transformation of molecular gas into stars, plus the energetics and evolution of the massive stars, sets some of the main characteristics of what we can observe, e.g. the interstellar medium chemical composition, the overall gas mass and the bolometric flux densities at different wavelengths. From the point of view of the Cosmic Ray community, the interest on star formation and what has been learned at infrared wavelengths is quite clear, since massive stars, their fast evolution and transformation into supernovae, is one of the main sources of cosmic ray acceleration.

This contribution will follow a similar path as that of the original oral presentation, starting with the star formation rate estimates from nearby clouds (§1), connecting these estimates with those obtained from the extrapolation of the SFR extragalactic indicators (§2), using then the concept of a high density molecular gas threshold to connect local and extragalactic measurements (§3), follow by the analysis of synthetic modeling of the SFR in the Milky Way (§4) and finally looking at what the latest far-infrared measurements of the Galactic Plane from Herschel are telling us on the SFR (§5).

Stars need to form from gas, and although this may seem too obvious today, it was Schmidt [27] nearly fifty years ago who suggested it, by looking at the distribution of the Population I stars in the Milky Way, that stars form from HI gas and that the rate of star formation (SFR) was proportional to the square of the volumetric gas density, i.e. \( SFR \propto \rho^2 \). Stars actually form in molecular clouds, where \( \text{H}_2 \) is the dominant specie, and this is quite relevant because there is not in our Galaxy or other extragalactic systems a one-to-one correlation between the spatial distribution of HI and that of \( \text{H}_2 \), in other words Schimdt did not get it quite right. Nevertheless, this prescription, allowed him to study fundamental properties of the Galaxy, like its luminosity function, the spatial distribution of stars and its chemical evolution [27].

Another key characteristic of the star formation process, it that the process itself seems to be different for low mass stars (0.1 - 8 \( M_\odot \)) and high mass stars (\( \geq 8M_\odot \)). And although there is a consensus on the main phases of the accretion process that leads to the formation low mass stars, this is not the case for high mass protostellar objects (see e.g. [1]).

2 From Local to Global Star Formation Rates and Efficiencies

A handful of studies have been published by the Galactic astronomers on the star formation rates (SFR) and efficiencies over the past three years that have tried to connect what is measured in the local molecular clouds with the results and rela-
tionships obtained by the extragalactic groups. The extragalactic scaling relations are of course based on the Schmidt-Kennicutt "law" that describes the star formation rate (per unit area) as a function of the gas mass of the system (gas surface density). Indeed, it is our understanding of what 'kind' of gas mass is truly involved in the star formation process, that has evolved since the time that Schmidt postulated a relation between the SFR as a power of the volumetric gas density of the neutral Hydrogen (HI) (see e.g. [12]).

The star formation process in nearby clouds, within 500pc or so from the Solar neighborhood, can be studied in great detail. Not only one can count the exact number of young stars that are formed in each cloud, but also one can determine their evolutionary stage, and therefore to have a complete picture of the process. One of the well known disadvantages of using the 'local' clouds, is that except for Orion, all of them are tracing the low mass star formation, with a median value of \( \sim 0.5 \text{M}_\odot \) over a time scale of \( \sim 2.1 \times 10^6 \text{ yr} \) [16]. Massive star formation does take place in the Milky Way, but the larger distances to these star forming regions, at least of couple of kiloparsecs away, skews our view of the star formation process towards the highest mass young stellar objects (see §4, Fig. 7), and therefore, our view still is incomplete.

**Fig. 1** The seven nearby star forming molecular clouds observed by the c2d team to determine their star formation rate (from Evans et al. [10]), defined by the extend of their extinction (grayscale) maps from \( A_V = 1 \) to 25 mag. The colored points correspond to the different classes of low mass young stellar objects, I (red), II (blue) and III (purple), within them.
One of the leading groups studying the star formation process taking place nearby is that of the Spitzer Legacy from Cores to Disk (c2d) (Evans et al. 10)]. This group not only have used the infrared detectors on board the Spitzer Space Telescope, but has supported their data with both optical, near-IR and sub-millimetric observations. The c2d group has analyzed the properties of five cold clouds (Cha II, Lupus, Perseus, Serpens and Ophiuchus; see Fig. 1) and found current star formation rates efficiencies ranging from 3% to 6%, with a accumulated rate of the five clouds of $2.6 \times 10^{-4} M_\odot yr^{-1}$. Even in this small sample of clouds, the variation in efficiency strongly suggests that the SF process changes from cloud to cloud. Furthermore, they found a star formation rate per unit area (or specific SFR) at least ten times larger than that predicted by extrapolating the extragalactic Schmidt-Kennicutt relation to their low mass range (see Fig. 2.), and they have interpreted this discrepancy as due to the fact that at large scales, like those in extragalactic systems, one includes both high and low density gas in the mass estimates (or gas surface density). This last conclusion was partially motivated by a previous study by Wu, Evans et al. [29], where a high gas density tracer, HCN J=1-0 (88.63 GHz), was used to measure the high density gas, rather than the standard CO J=1-0, to estimate the gas mass of Galactic dense cores, nearby spiral galaxies and farther away starburst galaxies. By using a high density gas tracer, they found a tight correlation over 7-8 orders of magnitude, between the IR luminosity, a direct tracer of the star formation activity, and the dense material, i.e. a Schmidt-Kennicutt type of relationship that connected the local SF activity in the MW with that of extragalactic systems, both normal and highly active.
Fig. 3 The cumulative mass profile of the clouds in Lada et al. [16] sample normalized to their corresponding number of YSOs as a function of infrared extinction. The eleven clouds reach a minimum at nearly the same magnitude $A_K = 0.8 - 0.9$mag, suggesting that there is a threshold in extinction at which the mass contained is the one most directly involved in the star formation of the cloud.

3 A High Density Molecular Gas Threshold for Star Formation

The Spitzer Legacy surveys were meant to provide a wealth of high quality IR data that could be used by a wider community to explore topics beyond those that were originally intended by the project. In the true spirit of taking advantage of the Legacy data, Lada, Lombardi & Alves [16] added the c2d clouds to their sample of star forming regions for extinction studies in the near infrared (NIR). NIR extinction has been successfully used to study the total mass of nearby clouds, as well as their structure. Some of the clouds in the extinction studies are relatively massive, e.g. the Pipe and California nebulae, but with very little star formation. The sample of extinction studied clouds doubled (11 clouds) that of the c2d group, and included some of the clouds forming massive stars like Orion A and B. The extinction method also allows a normalization of all the clouds to a given extinction threshold, and this idea is quite powerful since brings the studied molecular clouds on the same mass scale (see Fig. 3). Lada, Lombardi and Alves [16] found that when comparing the star formation inventories for these clouds with their extinction masses at a given threshold in the NIR K band (at $\sim 2.2\mu$m) of $A_K = 0.8$mag, there was a linear relationship between their SFR and the $M_{0.8}$ mass of the clouds, of the form $\text{SFR}(M_\odot\text{yr}^{-1}) = 4.6 \pm 2.6 \times 10^{-8} M_{0.8}$ (see Fig. 4).

This $A_K = 0.8$mag threshold corresponds to a gas surface density of $\Sigma = 116 M_\odot$pc$^{-2}$, and can be interpreted as a volumetric gas density threshold in molecular Hydrogen of $n(H_2) = 10^4$cm$^{-3}$. A similar threshold was determined by c2d group [11] using the local clouds, with $\Sigma = 129\pm14 M_\odot$pc$^{-2}$, where the Galactic SFR versus the gas mass of the parent cloud becomes linear and not very different than that of the extragalactic indicators (see Fig. 5). The nice physical interpretation of these results is that star formation takes place in the densest regions, above a given threshold, and when this is taking into account the SFR corresponds to that specific mass of dense gas. Indeed, Lada, Lombardi & Alves [16] suggested that if this is
Fig. 4 The number of YSOs as a function of the mass of the cloud set by the $A_K = 0.8$mag threshold (from Lada, Lombardi & Alves [16]), i.e. the mass of the dense gas directly involved with the star formation process.

![Figure 4](image1.png)

Fig. 5 The local Galactic star forming clouds do behave linearly in the specific star formation rate versus specific gas cloud density diagram, above a certain threshold ($\Sigma_{th}$), and not very different than the relationships found for the extragalactic indicators (see Heiderman et al. [11] for details).

![Figure 5](image2.png)

the case, then one should be able to place in the same relationship, SFR vs dense mass, Galactic Cores and extragalactic objects, and they explored this possibility in another study [17].

Figure 6 shows the SFR vs. cloud molecular mass for the local galactic clouds (circles), normal galaxies (pentagons), luminous (squares) and ultraluminous (inverted triangles) active star formation red galaxies (LIRGS & ULIRGS) plus high redshift BzK galaxies (triangles). The open symbols are for measurements of the gas mass based on CO observations ("mean" molecular masses), while the solid symbols are those based on a dense gas tracer (e.g. HCN) or extinction. The broken parallel lines correspond to constant fractions of the dense gas ($n(H_2) \geq 10^4$cm$^{-3}$).
and their slopes are those found by Lada, Lombardi & Alves [16]. If one takes into account that the CO mass measurements reflect an average on relatively large spatial scales in extragalactic systems (∼1 kpc), and corrects for this effect, such that the true mass involved in the star formation process (that of the dense gas) is included in the SFR-dense gas mass diagram, then local galactic molecular clouds and extragalactic system share the same relationship. According to Lada et al. [17], "there is a fundamental empirical scaling relation that directly connects the local star forming process with that operating globally within galaxies".

Fig. 6 The SFR-molecular cloud mass diagram according to Lada et al. [17]). Open symbols correspond to "mean" molecular gas masses, while the solid ones to those obtained for a dense gas either using extinction or HCN measurements (see text).

4 Synthetic Modeling of the Milky Way

When studying extragalactic systems, either nearby or at a high redshift, a common technique to interpret the observations is to compare them with synthetic models of a galaxy. In a model one can modify the Initial Mass Function and rate of star formation, plus add more information like a stellar spectra library to follow the spectral evolution of a system (see e.g. Bruzual & Charlot [4, 5]). Recently this technique has been applied by Robitaille & Whitney (2010) [24] to estimate the star formation rate of the Milky Way, based on a comparison with the mid-IR data obtained by GLIMPSE plus MIPSGAL (Churchwell et al. [8]; Carey et al. [6]), and as an extension to the thorough modeling carried out by Robitaille et al [22] of the spectral energy distribution (SED) of protostellar objects. For the Milky Way, Robitaille & Whitney [24] looked at the 3D distribution of star formation within the disk in such way to take into account not only their YSO theoretical SED models, but also including the limitations in sensitivity by the IRAC instrument as well as the
effects of dust extinction. Although the technique is quite powerful, it does depend on the assumptions of the model. The prescription of Robitaille & Whitney [22] goes as follows: distribute the YSOs in random positions, use random age and mass given by the Kroupa [15] Initial Mass function (within 0.1 to 50M$_\odot$), control the upper and lower stellar age, include a reasonable spatial distribution of dust, use the synthetic SEDs to estimate the intrinsic magnitudes and IRAC colors, select only those YSOs that fall within the survey area and fulfill the criteria of color and brightness defined by Robitaille et al. [23]; and finally, adjust the SFR to match the observations. In practice, only sources that are younger than 2Myr are used to really match the observations.

Figures 7 and 8 show the results for one of these models, the mass distribution function of the synthetic YSOs and their corresponding spatial distribution in the Milky Way, respectively. The red histogram of the mass distribution (Fig. 7) corresponds to what is actually observed, and this "represents to less than 0.5% of all the YSOs in the Galaxy" [24], i.e. the SFR is obtained from a very small fraction of objects. Also these YSOs are systematically more massive with a median value of 10-15M$_\odot$, but within a 3 to 20M$_\odot$ range. The spatial distribution (Fig. 8) is color coded according to extinction along the line-of-sight from us, and shows that most of the sources that are counted [23] are within 10-15 kpc from us.

After several "realizations" of the synthetic models, and taking into account that the contamination by AGB stars in the GLIMPSE & MIPSGAL sample ranges from 30% to 50%, the SFR in the Galaxy is estimated to be between 0.68 to 1.45M$_\odot$ yr$^{-1}$[24].

5 Far Infrared Star Formation Rate Estimate

The star formation rate estimated using mid-IR observations, like that using the synthetic models, does not take into account deeply embedded protostellar objects...
which are detected at wavelengths longer than 24\(\mu\)m, and this should not be a problem for the far-IR observations. Recently Veneziani et al. [28] have used data from the Herschel Space telescope of the HiGAL Key Project (Molinari et al. [20]) to estimate the rate of star formation in the Milky Way. The HiGAL KP surveyed the inner Galaxy \((l = \pm 60^\circ, b = \pm 1^\circ)\) using the PACS and SPIRE instruments in parallel mode, covering five wavelengths: 70, 160, 250, 350 and 500\(\mu\)m. At 70\(\mu\)m the angular resolution is 6\(\prime\prime\), while at 500\(\mu\)m is \(\sim 36\prime\prime\), and therefore, one of the biggest challenges of this type of survey is to correctly bandmerge the flux densities of the compact sources between short and longer wavelengths (Molinari et al. [21]). This is an issue because it is quite possible that many massive protostars deeply embedded are surrounded by low mass protostars when forming, and the long wavelength observations cannot resolve the multiple components (see e.g. [19]).

Veneziani et al. used the data from the so called Science Demonstration Phase (SDP), taken at two latitudes, \(l=30^\circ\) and \(l=59^\circ\), where the conditions of star formation are quite different. The \(l=30^\circ\) region is very active, including the well known W43 complex in its 2\(\prime\) field-of-view, while the \(l=59^\circ\) field looks into the Vulpecula region, tangent to a spiral arm [3]. For both of these fields there are very good estimates of the distances [25], so mass envelope and bolometric luminosities for the compact protostellar sources can be measured and be placed in the \(L_{BOL} vs M_{ENV}\) diagram (see e.g. [9, 19]). This diagram allowed Veneziani et al. [28] to follow the protostellar objects through their evolutionary tracks to their final zero age main sequence mass and count how many young stars per unit mass per unit time were found in the SDP fields. Preliminary results for the \(l=30^\circ\) field found 690 sources,
YSOs found in the l=30° SDP field place in the massive star formation bolometric luminosity ($L_{\text{bol}}$) vs. mass envelope ($M_{\text{env}}$) diagram (after Molinari et al. [19], Elia et al. [9]). The shaded region marks the range of envelope masses considered by Veneziani et al. [28] in their SFR estimate.

with $\sim 323$ being likely to be protostars, within a range of mass envelope of 80 to 2000$M_\odot$ and a median mass of 540$M_\odot$. These objects have a median evolutionary time of $\sim 2.5 \times 10^5$ yr and a median final main sequence mass of $\sim 15M_\odot$. Using Lada et al. [16] relationship for the star formation rate using the median mass and evolutionary time, one gets $\text{SFR} = \frac{N_{\text{YSOs}} \times M_{\text{final}}}{t_{\text{evol}}} \frac{M_\odot}{\text{yr}}$ or $323 \times 15 \times 2.5 \times 10^5 = 0.02M_\odot/\text{yr}$. This rate is approximately 20 times that of Orion A and B [16], perhaps too high to be representative of the entire Milky Way. This rate suggests that the simple method of counting protostellar objects is more complicated when dealing with high mass protostars, and that the number of YSOs identified plus their median final mass and lifetime under the "accretion" formation scenario can be a bit uncertain.

Given the relatively high luminosity at 70$\mu$m of the l=30° SDP field, and the fact that the selected YSOs were those found in the densest regions, Veneziani et al. [28] considered a second approach to estimate the SFR, by using an extrapolation of the FIR extragalactic indicator developed by Li et al. [18]. The Li et al. 70$\mu$m SFR indicator is based on a sample of 40 SINGs galaxies and uses 'sub-galactic' regions with sizes between 0.05 and 2 kpc, and in this sense closer to the scales that are sampled in the Milky Way. The indicator is calibrated for a range of 70$\mu$m luminosities of $5 \times 10^{40} \leq L(70) \leq 5 \times 10^{43}$ erg s$^{-1}$ and given by, SFR($M_\odot$/yr$^{-1}$) = $L(70)/1.067 \times 10^{43}$ erg s$^{-1}$. For the 70$\mu$m luminosity of the l=30° field, this corresponds to a SFR of $3.8 \pm 0.7 \times 10^{-4}M_\odot$ yr$^{-1}$.

If one assumes that HiGal l=30° tile is representative of the entire Milky Way, then is possible to have a rough estimate of the SFR rate in the Galaxy, by weighting the volume of each tile with respect to that of the Milky Way [28]. Approximating the Galaxy as a simple disk with a scale height of 100pc and a mean radius of 15kpc, the total mean star formation rate is $2.1 \pm 0.4 M_\odot$ yr$^{-1}$, i.e. within the range obtained by the synthetic modeling of the Milky Way.

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