The derivation of the evolutionary stage and rate of star formation of star-forming sites from Galactic single-dish far-infrared and submillimetre surveys suffers from the relatively limited spatial resolution that prevents access to ‘core’ scales ($r \lesssim 0.1$ pc) for heliocentric distances $d \gtrsim 1$ kpc. In a previous article, we studied the implications of this ‘distance bias’ for the mass–radius relationship and its ability to diagnose potential sites for high-mass star formation, using a method that simulates the appearance at large distances of nearby and well-resolved star-forming regions mapped with Herschel. In the present article, we use the same method to quantify the bias introduced in the estimate of the evolutionary stage of dense ‘clumps’ ($r \gtrsim 0.1$ pc) revealed from the Herschel Hi-GAL survey, focusing in particular on the $L_{\text{bol}}/M_{\text{env}}$ ratio, which is widely used as an evolutionary indicator. Furthermore, we discuss how the star formation rate (SFR) and efficiency (SFE) change with distance. The location of sources extracted from the virtual distance-displaced maps in the $L_{\text{bol}}$ versus $M_{\text{env}}$ diagram provides evolutionary indications that are consistent with those derived from the underlying population of cores and do not fluctuate substantially with distance. We also show that estimates of the SFR from integrated clump properties are consistent with estimates from the underlying resolved source population and show only minor variations with virtual distance. We conclude that methodologies commonly used to infer evolutionary indicators from clump-integrated quantities from large-scale single-dish Galactic far-infrared and submillimetre surveys are robust against distance and angular-resolution bias.

**Key words:** methods: statistical – stars: formation – ISM: clouds – infrared: ISM.

## 1 INTRODUCTION

The Herschel infrared Galactic Plane Survey (Hi-GAL: Molinari et al. 2010) mapped the entire Galactic Plane in five photometric bands at 70, 160, 250 and 350 and 500 μm, to investigate the initial phases of star formation over the Milky Way Galaxy (Elia et al. 2010, 2013, 2014; Beltrán et al. 2013; Olmi et al. 2013; Veneziani et al. 2013, 2017; Molinari et al. 2014, 2016; Schisano et al. 2014). Star-forming dust and gas condensations observed within Hi-GAL, as well as with other Galactic submillimetre surveys, cover a broad range of heliocentric distances (1 kpc $\lesssim d \lesssim 15$ kpc: Russell et al. 2011; Elia et al. 2017), therefore the physical sizes of the compact objects detected (i.e. not resolved or mildly resolved) span a wide range of linear scales. The so-called cores are the smallest compact sources ($D \lesssim 0.2$ pc: Bergin & Tafalla 2007) in the interstellar medium (ISM) and are the final result of the cloud fragmentation process, progenitors of single stars or binary/multiple systems. The largest compact objects in giant molecular clouds (GMCs) are the so-called clumps, which appear as compact sources with an unresolved internal structure, in the interior of which cores are contained. The typical diameter of clumps is $0.2 \lesssim D \lesssim 3$ pc (Bergin & Tafalla 2007). The main physical properties of these sources, such as radius, mass and luminosity, are found to span a wide range of values.

Herschel was not capable of resolving the internal structure of the clumps for distant sources (e.g. Elia et al. 2013; Baldeschi et al. 2017), hence only average properties can be used to describe the physical conditions of a source and to identify possible signatures of star formation taking place in its interior.

Large-scale panoramic surveys of the Milky Way in the infrared and submillimetre have proved very powerful tools, as they allow us to tackle star formation as a global process and with unprecedented statistical significance. Such surveys, however, are only feasible with single-dish facilities with optimized mapping capabilities, such as Herschel (Pilbratt et al. 2010) or APEX, which allow access to sub-arcmin spatial scales that are insufficient to trace the linear scales of ‘cores’ when the object distance is above 0.5–1 kpc. It is
therefore important to understand and characterize how the estimate of physical and evolutionary parameters at ‘clump’ level relate to the properties of the underlying population of cores and how these estimates change with the heliocentric distance of the sources.

This article is the second of a series of articles intended to describe the effects of this, which can be called a ‘distance bias’. Baldeschi et al. (2017), hereafter Paper I, discussed how the distance bias affects estimates of the physical properties of compact objects, with particular regard to the classification of a source as a high versus low-mass star-forming site. Here, we discuss how such bias affects the evolutionary classification of compact objects and the estimate of the star formation rate (SFR) and efficiency (SFE).

In recent literature (Gianinni et al. 2012; Fallscheer 2012; Elia et al. 2013; Veneziani et al. 2013, 2017; Molinari et al. 2016), the luminosity versus mass diagram has been used to infer the evolutionary status of compact sources through comparison with theoretical tracks obtained from Molinari et al. (2008).

In this article, we aim to understand whether the evolutionary status estimated for clumps bears a resemblance to the properties of the underlying core population. One important indicator to highlight distinct phases of star formation in massive protostellar clumps is the $L_{bol}/M_{env}$ ratio (Molinari et al. 2016; Elia et al. 2017); here we discuss the relation of this indicator for clumps to the internal population of cores.

To reach this goal, we follow the method of Paper I, in which we took Herschel maps of the Lupus, Perseus, Serpens and Orion A nearby star-forming regions from the Gould Belt survey (HGBS: André et al. 2010), where compact sources correspond to dense cores, and degrade their resolution to mimic views of the same regions if they were located at a larger heliocentric distance.

In this way, we can estimate the degree of information lost as a function of distance and hence the bias affecting the estimate of Hi-GAL compact source physical properties. Each of the nearby regions considered is displaced to a set of different virtual distances. At each virtual distance, we repeated the typical procedures applied to Hi-GAL maps for extracting compact sources and derived their physical properties (e.g. Elia et al. 2013), treating the simulated maps as a completely new data set, with no reference either to the original map or to those ‘displaced’ at other distances.

The article is organized as follows. In Section 2 we present the regions of the Gould Belt survey and summarize the procedure used to ‘displace’ the maps and estimate the main physical parameters of compact sources. Section 4 shows how the distance biases the estimation of the evolutionary status of the sources. Section 5 shows how the SFR and SFE estimates change with distance. Finally, in Section 6 we summarize the conclusions of the article.

2 OBSERVATIONS AND METHODOLOGY

In this section, we present the observations considered and the methodology. Since they are already shown in Paper I, here we provide a brief summary.

2.1 Observations and data reduction

As in Paper I, we focus on a few of the Gould Belt regions, namely Orion A, Perseus, Serpens, Lupus III and IV. Orion A is known to be a high-mass star-forming region and Perseus and Serpens are intermediate- to low-mass star-forming regions, while Lupus III and IV are forming only low-mass stars.

Observations were taken at a scan speed of 60 arcsec s$^{-1}$ in parallel mode with the two cameras Photoconductor Array Camera and Spectrometer (PACS) (Poglitsch et al. 2010) and Spectral and Photometric Imaging Receiver (SPIRE) (Griffin et al. 2010); the observed wavelengths were 70 and 160 µm for PACS and 250, 350 and 500 µm for SPIRE, respectively. Maps were generated for both instruments with the UNIMAP code (Piazzo et al. 2015). We assumed the following distances to the regions: 50 and 200 pc (Comerón 2008) for Lupus IV and III, respectively; 235 pc (Hirota et al. 2008) for Perseus; 230 pc for Serpens (Éiroa, Díupvik & Casali 2008); 415 pc for Orion A (Menten et al. 2007).

As already described in Paper I, these regions will be the subject of dedicated articles to be published by the HGBS consortium: therefore we do not provide any source catalogue for them here.

2.2 The simulation of increased distance

Briefly, the methodology developed by Paper I to simulate the appearance of a nearby star-forming region mapped with Herschel as if it were at a distance larger than the real one (virtual distance) consists of the following.

(i) Rescaling/rebinning the original map by a factor $d_0/d$, where $d_0$ and $d$ are the ‘true’ and ‘displaced’ distances, respectively.

(ii) Convolving the new rescaled map with the point spread function (PSF) of the instrument at the given wavelength.

(iii) Adding white Gaussian noise to the map to restore the original noise level.

We ‘displace’ each region at each wavelength to the following distances: 0.75, 1, 1.5, 2, 3, 5 and 7 kpc. Once we displaced the maps, we applied the standard Hi-GAL procedure (Elia et al. 2013, 2017) to detect compact sources and extract their physical properties. Here, we briefly summarize the main steps.

The detection and photometry of compact sources on the original and ‘displaced’ maps are carried out with the Curvature Thresholding Extractor (CUTEX: described in Molinari et al. 2011). The CUTEX set-up (input parameters) is described in Paper I as well as in Molinari et al. (2016) and the leading output parameters are peak position, minimum and maximum full width at half-maximum (FWHM: $\phi_{min}, \phi_{max}$) of the fitting ellipse, peak flux and integrated flux. The measured fluxes are then corrected with the pipeline described in Pezzuto et al. (2012), since the PSF of PACS and SPIRE is not a perfect Gaussian.

After the flux measurement in all five Hi-GAL wavelengths, we band-merged the counterparts at different bands based on positional association and derived a list of ‘reliable compact source candidates’, the spectral energy distributions (SEDs) of which must satisfy the following criteria: (1) detections in at least three consecutive wavebands between 160 and 500 µm, (2) having a concave shape, (3) not peaking at 500 µm.

The next step is the modified blackbody fit (hereafter greybody fit, e.g. Elia et al. 2013, 2017), described by the equation

$$F_\nu = \frac{M}{4\pi d^2} k_\nu \left( \frac{v}{v_0} \right)^\beta B_v(T),$$

where $F_\nu$ is the flux at frequency $\nu$, $M$ is the dust mass of the source located at distance $d$, $k_\nu$ is the opacity at the frequency $\nu_0$, where we adopt $k_\nu = 0.1$ cm$^2$ g$^{-1}$ at $v_0 = 1000$ GHz ($\lambda_0 = 300$ µm, Beckwith et al. 1990), and $B_v(T)$ is the Planck function at temperature $T$. We fixed $\beta$ at 2 as in Elia et al. (2013). The flux at 70 µm, where present, is not considered for the fit, since it is due mostly to the protostellar content of a clump, rather than its large-scale envelope emitting as a greybody (Elia et al. 2013). Sources are classified as protostellar if the 70-µm counterpart is present or starless if it is not present (Elia et al. 2017).
et al. 2013). Starless objects are subsequently classified as bound (prestellar objects) if they fulfil the Larson relation (Larson 1981):

\[ M_{\text{Lar}} \geq \frac{460}{M_\odot} \left( \frac{r}{\text{pc}} \right)^{1.9}, \]  

(2)
or unbound if they do not.

The mass estimated through the fit represents the real mass for prestellar objects and the envelope mass for protostellar ones (Elia et al. 2013). The greybody provides the estimates of \( T \) and \( M \), while the bolometric luminosity \( L_{\text{bol}} \) is estimated as described in Yun et al. (2015).

### 3 CHARACTERIZATION OF THE FLUX OF DISPLACED SOURCES

Before discussing the luminosity versus mass diagram, we want to discuss the flux of the displaced sources in relation to the flux of the sources detected at the original distance. This relation was discussed extensively in Paper I; here we will add a short section to complete what was previously claimed.

In Paper I, we have seen that if we compare the flux of the displaced clumps at distances \( d \geq 3 \text{ kpc} \) with the flux of the embedded cores, \(^1\) it is found that 80–90 per cent of the flux of the clumps comes from the diffuse intercore material for 160, 250, 350 and 500 \( \mu \text{m} \), while this fraction decreases to 50–60 per cent at 70 \( \mu \text{m} \). This effect is due mostly to the very different background levels used for the source photometry with the displacing distance (Paper I).

Therefore, the comparison among measurements with source extraction performed with the same methodology at the native and displaced distance made in Paper I is misleading if interpreted as the fraction of emission in cores over the clump total, as the reference in the two measurements is so very different. It is true, however, that the source physical and evolutionary parameters we derive from the data (\( L_{\text{bol}}, M_\text{env} \) and \( L_{\text{bol}}/M_\text{env} \), for example) are based on the observed fluxes, so clearly the more distant the detected clumps, the lesser the contribution of emission coming from the embedded cores compared with the total measured clump fluxes. However, this is mostly true for the clump mass, because we have seen that this problem mainly affects fluxes longward of 100 \( \mu \text{m} \), which are the ones used to determine the dust mass. As the clump bolometric luminosity becomes more and more dominated by the mid- and near-IR portions of the SED, the distance effect becomes less and less relevant, since the cores-to-clump emission contribution, already around 50 per cent at 70 \( \mu \text{m} \) (Paper I), increases more and more with decreasing wavelength. Therefore we conclude that the \( L_{\text{bol}}/M_\text{env} \) parameter is a good tracer of the average evolution of dense cores in clumps.

Interestingly, clumps detected in the displaced maps generally coincide with active star-forming regions in the original ones and do not include significant cirrus emission. We show an example of that in Fig. 1, in which we display a piece of the original Perseus map at 250 \( \mu \text{m} \) with the ellipse of a clump detected at 7 kpc. All pixels within the ellipse of the clump are above the background and vice versa for pixels outside the ellipse. This behaviour is also found systematically for most clumps in other regions.

Starting from the column density maps, which were obtained by fitting greybody spectral energy distributions in each pixel of the data (Paper I), and a young stellar object (YSO) is the diagram showing the relation between bolometric luminosity \( L_{\text{bol}} \) and envelope mass \( M_\text{env} \). Different positions in this diagram correspond to different evolutionary stages: Saraceno et al. (1996) used this diagram to clarify the evolutionary stage of low-mass YSOs, while Molinari et al. (2008) extended this diagram to the high-mass regime (clumps), adopting the model developed by McKee & Tan (2003).

In a first phase, the object is accreting and the luminosity increases almost vertically in the \( L_{\text{bol}} - M_\text{env} \) diagram, while the mass decreases slowly because part of the material accretes on to the embedded protostar and is expelled through jets of matter. At the end of the first phase, the star reaches the zero-age main sequence\(^2\) (ZAMS) and starts the second phase, where the luminosity remains almost constant while the envelope mass decreases, as it is cleared out by powerful winds from newborn ZAMS stars.

A more compact way to express the relation between these two quantities is their ratio \( L_{\text{bol}}/M_\text{env} \) (Ma, Tan & Barnes 2013; Urquhart et al. 2014; Molinari et al. 2016; Elia et al. 2017), in both ascending and horizontal parts of the evolutionary tracks. Indeed, larger values of this ratio correspond to later evolutionary stages. Molinari et al. (2016) calibrated the \( L_{\text{bol}}/M_\text{env} \) ratio against the clump gas temperature and showed that, when \( L_{\text{bol}}/M_\text{env} \lesssim 1L_\odot/M_\odot \), the gas temperature is below \( T \sim 35 \text{ K} \), suggesting

\(^1\) To compare the flux of the displaced clumps properly with the flux of the embedded cores, we have to rescale the flux to the original distance by multiplying it by \( (d/d_0)^2 \).

\(^2\) This is true only in the high-mass regime (\( M > 8M_\odot \)).
Bias in SFR and evolutionary status

Figure 2. $L_{\text{bol}}$ versus $M_{\text{env}}$ diagram for the Orion A region. Red and blue circles are prestellar and protostellar sources, respectively, at the original distance and are shown in all panels for reference. Triangles correspond to the objects detected in the ‘displaced’ maps at different virtual distances (panels b–i). The solid grey and black curves are evolutionary tracks for the low- (Saraceno et al. 1996) and high-mass regimes, respectively (Molinari et al. 2008). The solid green lines represent ratio $L_{\text{bol}}/M_{\text{env}}$ equal to 1 and 10.

To summarize the distance effects in this plot in a more compact view, in Fig. 3 we display the median bolometric luminosity versus the median envelope mass for each region considered at each distance. Note that the ratio of the median values of $L_{\text{bol}}$ and $M_{\text{env}}$ is approximately constant with distance for protostellar objects for each of the considered regions, suggesting that the $L_{\text{bol}}/M_{\text{env}}$ indicator can be considered as a robust tool to trace the evolutionary status of protostellar sources.

The Orion A region, as it appears in Fig. 3 (yellow line), has higher $L_{\text{bol}}/M_{\text{env}}$ and so appears more evolved than the other molecular clouds. This is true at the original distance and also at the virtual distances (see Fig. 3, upper panel). This indicates that clumps containing more evolved cores are typically classified, in turn, as more evolved.

This view is supported further by the relation between properties of clumps detected at the largest probed distance and those of contained sources at smaller distances. To analyse this point, we adopt the same procedure described in Paper I and briefly summarized in the following.

Let $O_{d_{\text{max}}}$ be a protostellar source detected at the largest virtual distance $d_{\text{max}}$ and $O_d$ the protostellar and starless sources at distance $d_0 \leq d < d_{\text{max}}$ ‘contained’ within $O_{d_{\text{max}}}$: we project the ellipse...
corresponding to $O_{\text{d}z}$ back to distance $d$ and consider the sources that fall within the ellipse. Figs 4–6 display the position of $O_{\text{d}z}$ in the $L_{\text{bol}}$ versus $M_{\text{env}}$ diagram and the corresponding $O_{\text{d}z}$ for Orion A, Perseus and Serpens. The sources detected at the original distance in Orion A (Fig. 4) appear to be, on average, more evolved than the sources in the other regions at the original distance (Figs 5–6) and also, importantly, the $O_{\text{d}z}$ of Orion A are still more evolved than those of Perseus and Serpens. Therefore the estimated evolutionary status of a clump is related to that of one of the embedded cores: clumps with a high value of $L_{\text{bol}}/M_{\text{env}}$ will most likely have a contained cores population with, on average, a higher value of $L_{\text{bol}}/M_{\text{env}}$ compared with a low $L_{\text{bol}}/M_{\text{env}}$ clump. Hence, as a general trend, more evolved cores are associated with more evolved clumps.

**5 STAR FORMATION RATE AND EFFICIENCY**

**5.1 Star formation rate**

One of the most important parameters for characterizing a galaxy or a star-forming region is its rate in turning gas and dust into stars, namely its star formation rate (SFR). In this section, we want to understand how the SFR estimate of a given region is affected by distance. For nearby regions ($d < 1$ kpc), such as Perseus, Serpens, Orion A and Lupus, the standard method consists of assuming
Bias in SFR and evolutionary status

that the SFR is proportional to the YSO population in the cloud. A representative YSO mass and star formation time-scale are generally assumed, so that the total SFR can be estimated by just summing up the contribution of all objects. In the regions investigated by Evans et al. (2009) and Lada, Lombardi & Alves (2010), formation times of $2 \pm 1 \times 10^6$ yr and a YSO median mass of $0.5 M_\odot$ are adopted, so that the total SFR is given by

$$SFR = 0.25 \, N(YSOs) \, M_\odot \, \text{Myr}^{-1},$$

(3)

where $N(YSOs)$ is the number of YSOs in the region. We will propose below a modification of this prescription.

Since the typical distances of the Hi-GAL compact sources are $d \geq 1$ kpc (Elia et al. 2017), equation (3), which can be used only for resolved YSOs, can no longer be used, because at these distances the compact objects are clumps that host embedded clusters of YSOs. In this regime, the $L_{bol}$ versus $M_{env}$ diagram has been used by Veneziani et al. (2017) to quantify the SFR of a protostellar clump once its mass is known. In short, upgrading an earlier prescription from Veneziani et al. (2013), the clump mass is compared with the set of evolutionary tracks from Molinari et al. (2008), but in this case the clump, instead of a single forming massive star, hosts a cluster with mass distribution simulated using Monte Carlo realizations of a cluster following the initial mass function (IMF) of Kroupa (2001) and producing the same bolometric luminosity typically observed for clumps of the same total mass, but associated with ultracompact H II regions. Through this method, for each clump in each region and at each virtual distance, one can then derive an estimate of the SFR: how do these SFR values change with virtual distance and how do they compare with the SFR estimated at their true distance?

The first step is to compute the SFR at the true distance. To do that, one needs to combine the Herschel data with the Spitzer data to get the complete census of YSO populations. Indeed, Herschel mainly traces Class 0 and I YSOs (usually called protostellar cores, e.g. Giannini et al. 2012; Rygl et al. 2013), while Spitzer is mostly sensitive to Class II and III YSOs. Therefore, we took the Spitzer YSO lists for Perseus and Serpens from the c2d Spitzer Legacy project (Evans et al. 2009) and those for Orion A from Megeath et al. (2012). Since Herschel did not scan exactly the same sky area covered by Spitzer, we combined the data in the common sky area and, obviously, objects in common between Herschel and Spitzer were counted once for the estimation of the SFR, using equation (3).
Figure 8. Sum of the SFR of the clumps for each of the considered distances versus the sum of the SFR of the YSOs (Spitzer and Herschel) embedded within the clumps, estimated through equation (3) for each of the considered distances. The size of the dots increases with distance. Solid line: bisector of the plot. Dashed black lines: reference lines with slope 1.5 and 10, respectively. Dashed green line: median line with slope 3.7. We do not show the SFR embedded YSOs [M⊙/Myr] versus the sum of the SFR of the YSOs (Spitzer and Herschel) inside the clumps, estimated through equation (3) for each of the considered distances. The size of the dots increases with distance. Solid line: bisector of the plot. Dashed black lines: reference lines with slope 1.5 and 10, respectively. Dashed green line: median line with slope 3.7. We do not show Lupus III and IV, due to the lack of protostellar objects.

The second step consists of estimating the SFR at the ‘displaced’ distances using the procedure of Veneziani et al. (2017). After that, we have to compare the SFR of the protostellar clumps detected in the ‘displaced’ maps with the SFR of the contained Herschel+Spitzer YSO population only (Fig. 7). To do that, in Fig. 8 we show the SFR derived from protostellar clumps versus the total SFR, estimated through equation (3), of the YSOs contained inside the ellipses representing the clump, once reported at the original distance.

We notice that the SFR of the clumps is larger (at each distance and for all the regions) by a factor between 1.5 and 10 than the SFR of the underlying core population.

However, a revision of equation (3) is needed, in our case, because here we are extending the YSO census of the star-forming regions considered to Class 0, thanks to Herschel, and we are considering only those YSOs spatially associated with the projected areas of the clumps in the distance-displaced maps. Indeed, we verified that the median value of the luminosity distribution of the YSOs within the back-projected clump areas is larger, at each virtual distance, than the median luminosity of the objects outside the clump areas. For example, the median luminosity of the Spitzer YSOs included in clump regions at a virtual distance of 2 kpc is 0.245 L⊙, while the median luminosity of the Spitzer YSOs not included in these clumps is 0.07 L⊙. Since we know that more luminous objects are also usually more massive and short-lived, the SFR associated with a massive object turns out to be larger than the SFR associated with a smaller object: this may suggest that equation (3) is probably not the best choice to estimate the SFR of objects embedded in clumps, because it was derived considering the global properties of molecular clouds.

To take these effects into account, we build the luminosity distribution for the Spitzer sources contained within the back-projected clump areas. For each value of the luminosity, we use the evolutionary tracks of Palla & Stahler (1999) to derive a potential range of stellar masses that could correspond to those luminosities. Therefore, for each bin of the luminosity distribution histogram, we derive the corresponding specific range of masses [M_{min}, M_{max}] and, assuming the IMF of Kroupa (2001), we carry out a Monte Carlo realization of YSO masses within this range. For each region considered, we repeat this procedure for each bin of the luminosity distributions derived for the YSO populations underlying the back-projected clump areas from each virtual distance. The evolutionary tracks of Palla & Stahler (1999) also provide an estimate of the time taken for these objects, starting from the birthline, to reach the ZAMS, so that, for each YSO mass range in the above procedure, we also associate an average time-scale to reach the ZAMS from the birthline.

By doing that, we obtain a median mass and a median lifetime (for each distance) and hence we can modify equation (3) to estimate the SFR. We find that the median YSO mass in the back-projected clump area is almost independent of the virtual distance and is \( \sim 0.39 M_\odot \), while the median lifetime is independent of distance and assumes the value of \( \sim 0.8 \) Myr. Once we have the median mass and the median lifetime, we can modify the coefficient 0.25 of equation (3) with 0.39/0.8 = 0.49. Therefore the equation that we obtain to estimate the SFR of the Spitzer YSOs contained within back-projected areas of clumps is

\[
SFR_{\text{Sp}} = 0.49 \, N(\text{YSOs}) \, M_\odot \, \text{Myr}^{-1}. \tag{4}
\]

We repeat the same procedure, with the same tracks, for the Herschel protostellar cores\(^4\) to obtain a formula to estimate the SFR. In this case, we get a median mass almost independent of virtual distance, 1 M⊙, and a median lifetime (independent of distance) of 0.8 Myr, corresponding to

\[
SFR_{\text{H}} = 1.2 \, N(\text{cores}) \, M_\odot \, \text{Myr}^{-1}. \tag{5}
\]

We can now estimate the SFR of the YSOs contained in back-projected areas of clumps using equation (4) for the Spitzer YSOs and (5) for the Herschel protostellar cores, so that SFR = SFR_{\text{Sp}} + SFR_{\text{H}}. Fig. 9 displays the total SFR of the protostellar clumps versus the total SFR of the contained YSOs using equations (4) and (5). We see that the SFR of the clumps is now comparable in most cases with the SFR of the contained cores. Plotting the ratio between the SFR of clumps and the SFR of the embedded YSOs as a function of distance (Fig. 10), we find that there is no specific trend of this ratio with distance, so that, as a combination of various effects discussed above, the distance seems not to introduce any bias.

It is also important to understand whether the global SFR estimated at the displaced distances (again through the procedure of Veneziani et al. 2017) is constant with \( d \) or not. In Fig. 11, we show the total SFR for each of the regions considered for each of the virtual distances: one can see that the SFR is almost constant with \( d \). We can explain the behaviour of the SFR being constant with distance through the following considerations: as the distance increases, the sizes and masses of the detected compact sources increase.

\(^3\) We used only the YSOs of the Serpens and Perseus region (Evans et al. 2009), since, in the Orion A catalogue provided by Megeath et al. (2012), the bolometric luminosity of the YSOs is not present.

\(^4\) Obviously, we cannot use the masses derived from the greybody fit, since they represent the masses of the dust envelope and not the contained protostar, therefore we use the simulated masses derived from the Palla & Stahler (1999) model.
Bias in SFR and evolutionary status

5.2 Star and clump formation efficiency

The efficiency at which the molecular clouds turn their gas into stars is a fundamental part of the star formation process that Hi-GAL data can address. This matter was raised by Elia et al. (2013), but no discussion of a possible distance bias was provided in that work. Here, we want to study how the clump formation efficiency (CFE) and star formation efficiency (SFE) change with distance. Indicating the total mass of the Herschel compact sources (both protostellar and starless) as $M_{\text{cl}}$ and the total cloud mass as $M_{\text{gas}}$, the CFE is defined as $\text{CFE} = M_{\text{cl}} / (M_{\text{cl}} + M_{\text{gas}})$. To estimate the fraction of mass of clumps converted into stars (SFE), we use

$$\text{SFE} = \frac{\epsilon_{\text{ff}}\epsilon_{\text{cc}}M_{\text{pro}}}{\epsilon_{\text{ff}}\epsilon_{\text{cc}}M_{\text{pro}} + M_{\text{gas}}},$$

where $M_{\text{pro}}$ is the sum of masses of protostellar clumps in the considered region, $\epsilon_{\text{ff}}$ is the core to star formation efficiency, which we assume equal to 0.33 (Alves, Lombardi & Lada 2007), and $\epsilon_{\text{cc}}$ is the clump to core formation efficiency.

The value of $\epsilon_{\text{cc}}$, as we have seen in Paper I, depends on the distance below 1500 pc and it starts to be approximately constant for larger distances. We assumed that $\epsilon_{\text{cc}}$ is 0.15, 0.15, 0.15, 0.15, 0.2, 0.3 and 0.4 at 7000, 5000, 3000, 2000, 1500, 1000 and 750 pc (Paper I). The SFE at the original distance can be estimated from equation (6) by assuming $\epsilon_{\text{cc}} = 1$, since, at the native distance, the compact sources detected are cores and not clumps. The cloud mass $M_{\text{gas}}$ can be estimated from the column density maps.

We start our analysis with the CFE. In Fig. 12, we show the CFE for each of the regions considered, namely Orion A, Perseus and Serpens. The CFE appears to fluctuate with distance, usually within a factor of 2, increasing slightly with distance for the Perseus region in particular. Indeed the CFE at the original distance is $\sim 0.06$ for each of the considered regions, while it is $\sim 0.11, 0.15$ and $0.22$ for Serpens, Orion A and Perseus, respectively, at the largest probed distance of 7 kpc.

For estimation of the SFE, we have to account not only for class 0 and protostellar sources, generally traced by Herschel, but also...
also for the more evolved class I–II, mostly traced by Spitzer. In Fig. 13, we display the ratio between the SFE of the ‘displaced’ protostellar clumps, computed according to equation (6), and the SFE of the Herschel and Spitzer YSOs embedded in those clumps at the original distance. We assume that each of the Spitzer sources embedded in these clumps, as we have seen in Section 5.1, has a mass of 0.49 $M_\odot$. The SFE, at the native distance, of the Spitzer and Herschel YSOs embedded in the clumps is estimated with

$$SFE_{d_0} = \frac{M_{\text{prot}+\text{fit}} + M_{\text{pos}}}{M_{\text{prot}+\text{fit}} + M_{\text{pos}} + M_{\text{gas}}}.$$  

6 This is the median mass of Spitzer YSOs embedded in the clumps that we obtained from the Palla & Stahler (1999) model, as described in section 5.1.

where $M_{\text{prot}+\text{fit}}$ is the total mass of the embedded Herschel cores, while $M_{\text{pos}}$ is the total mass of the embedded Spitzer YSOs. In Fig. 13, we see that not only is this ratio almost constant with distance, but it is also close to 1, indicating that the SFE estimated with Herschel is a reliable estimate of the SFE as it would be estimated by observing the same region at nearby distances. Therefore we can conclude that the distance bias affects the estimate of the SFE weakly for Hi-GAL observations.

6 CONCLUSIONS

The progressive loss of physical spatial resolution with kinematic distance in Galactic plane single-dish far-IR and submillimetre surveys influences estimates of the physical parameters (mass, temperature, radius and luminosity) that can be derived from the data (Baldeschi et al. 2017). Our ability to derive evolutionary diagnostics of dense star-forming clumps from these data is therefore also impacted. This is true for the Herschel Hi-GAL survey, in particular, since the sensitivity of the PACS and SPIRE cameras allows detection of compact far-IR sources at distances well above 10 kpc. To estimate the extent to which our ability to diagnose different evolutionary stages in Galactic star formation from Herschel data is preserved with distance, we used Herschel maps at 70, 160, 250, 350 and 500 $\mu$m from the Lupus, Perseus, Serpens and Orion A nearby star-forming regions observed in the Gould Belt programme; we displaced them at different distances (up to 8 kpc) with a noise-preserving degradation technique and ran source extraction and science analysis to verify the effects of distance on the derived physical parameters. The main results are as follows.

(i) The global evolutionary status determined from the location of the clumps in the $L$–$M$ diagram carries information that is consistent with the distribution in the same diagram of the underlying cores measured at the native distance. This confirms the result of Paper I that the clumps at any virtual distance are dominated by cores of the same nature (pre-proto-stellar). The $L_{\text{bol}}/M_{\text{env}}$ indicator can then be considered as a robust tool to highlight distinct phases of star formation in massive clumps, since it fluctuates weakly with distance for any given region analysed.

(ii) The star formation rate estimated from Herschel data at large distances ($d \geq 1$ kpc: Veneziani et al. 2017) can be considered almost constant with $d$, in the sense that if a region, located at distance $d_1$, were displaced to a distance $d_2 > d_1$ then one would estimate a similar SFR within a factor of 2.

(iii) The SFR of the clumps estimated at large distances with the method of Veneziani et al. (2017) is found to be comparable within a factor of 2 with the SFR estimate from the maps at native distance using standard YSO counting methods.

(iv) The SFE is approximately constant with distance, while the CFE tends to increase slightly with $d$.

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APPENDIX A: LUMINOSITY VERSUS MASS DIAGRAMS

In Figs A1–A4, we display the luminosity versus mass diagrams for Perseus, Serpens, Lupus III and Lupus IV, respectively, for both original and virtual distances.
Figure A1. Same as Fig. 2 but for the Perseus region.
Figure A2. Same as Fig. 2 but for the Serpens region.
Figure A3. Same as Fig. 2 but for the Lupus III region.
Figure A4. Same as Fig. 2 but for the Lupus IV region.