Tracing the Energetics and Evolution of Dust with Spitzer: a Chapter in the History of the Eagle Nebula

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\textbf{ABSTRACT}

\textbf{Context.} The Spitzer GLIMPSE and MIPS GAL surveys have revealed a wealth of details of the Galactic plane in the infrared (IR). We use these surveys to study the energetics and dust properties of the Eagle Nebula (M16), one of the best known SFR. Aims. We present MIPS GAL observations of M16 at 24 and 70 \( \mu \)m and combine them with previous IR data. The mid-IR image shows a shell inside the well-known molecular borders of the nebula. The morphologies at 24 and 70 \( \mu \)m are quite different, and its color ratio is unusually warm. The far-IR image resembles the one at 8 \( \mu \)m that enhances the structure of the molecular cloud and the Pillars of creation. We use this set of data to analyze the dust energetics and properties within this template for Galactic SFR.

\textbf{Methods.} We measure IR SEDs across the entire nebula, both within the shell and the PDRs. We use the DUSTEM model to fit these SEDs and constrain dust temperature, dust size distribution, and interstellar radiation field (ISRF) intensity relative to that provided by the star cluster NGC6611.

\textbf{Results.} Within the PDRs, the dust temperature, the dust size distribution, and ISRF intensity are in agreement with expectations. Within the shell, the dust is hotter (~70 K) and an ISRF larger than that provided by NGC6611 is required. We quantify two solutions to this problem. (1) The size distribution of the dust in the shell is not that of interstellar dust. (2) The dust emission arises from a hot (~10^6 K) plasma where both UV and collisions with electrons contribute to the heating.

\textbf{Conclusions.} We suggest two interpretations for the M16s inner shell. (1) The shell matter is supplied by photo-evaporative flows arising from dense gas exposed to ionized radiation. The flows renew the shell matter as it is pushed out by the pressure from stellar winds. Within this scenario, we conclude that massive star forming regions such as M16 have a major impact on the carbon dust size distribution. The grinding of the carbon dust could result from shattering in grain-grain collisions within shocks driven by the dynamical interaction between the stellar winds and the shell. (2) We also consider a more speculative scenario where the shell would be a supernova remnant. We would be witnessing a specific time in the evolution of the remnant where the plasma pressure and temperature would be such that the remnant cools through dust emission.

\textbf{Key words.}

1. Introduction

The Eagle Nebula (M16) is a nearby (d = 2.0 \pm 0.1 kpc, [Hillenbrand et al. 1993]) massive star forming region made a sky icon by the publication of spectacular Hubble Space Telescope (HST) images of the ionized gas emission [Hester et al. 1996]. As one of the nearest star forming region and one of the most observed across the electromagnetic spectrum, the Eagle Nebula is a reference source. The nebula cavity is carved into the molecular cloud by a cluster of 22 ionizing stars earlier than B3 (Dufton et al. 2006b) and with an estimated age of 1–3 \times 10^6 yrs [Hillenbrand et al. 1993; Dufton et al. 2006b; Martayan et al. 2008].

The mid-IR images of M16 either from the Infrared Space Observatory Camera (ISOCAM; Cesarsky et al. 1996a) at 8 and 15 \( \mu \)m (Pilbratt et al. 1998; Omont et al. 2003) or based on the combined Spitzer observations using IRAC 8 \( \mu \)m (Fazio et al. 2004) and MIPS 24 \( \mu \)m (Rieke et al. 2004), show a shell-like emission at 15 and 24 \( \mu \)m that fills the nebula cavity [Flagey et al. 2009a], as delineated by the shorter IR wavelengths and the extent of the \( \text{H}_\alpha \) emission. The shell stands out in the ISO 15 \( \mu \)m and MIPS 24 \( \mu \)m images, while the Nebula pillars, and the outer rim of the nebula are the strongest emission features at 8 \( \mu \)m. Based on some spectroscopic evidence (Urrutxut et al. 2003), we know that the mid-IR shell emission arises from dust with only a minor contribution from ionized gas lines to the broadband emission.

M16 is not alone in this respect. There are other large, partially symmetrical and rich HII regions (in terms of their OB stellar content) that display a similar mid-IR color stratification: the Rosette Nebula (Kraemer et al. 2003), the Trifid Nebula (Lefloch et al. 1999; Rho et al. 2006), and M17 (Povich et al. 2007). Furthermore, the multi-wavelength observations of the HII regions in the Galactic Plane, using the Spitzer GLIMPSE and MIPS GAL Legacy surveys (Churchwell et al. 2006).
by the expanding nebula. Collisional excitation by hot elec-
trons contribute significantly to the heating of dust. Infrared
dust is constantly replenished by photo-evaporation of high
time is shorter than the expansion timescale. It requires that

What are these Spitzer images of massive star forming
regions teaching us about dust and the interaction of the
stars with their environment? The IRAC and the MIPS
24 µm camera are imaging the emission from PAHs and Very
Small Grains (VSGs). A first key to the interpretation of
Spitzer images is the change in abundance and excitation of
these small dust particles from molecular to ionized gas.
Observations of nearby molecular clouds illuminated by O
stars, where observations separate the H II photo-ionized
gas layer from the neutral Photo-Dissociation Region (PDR)
show that the PAH bands, which are a characteristic of PDR
mid-IR emission spectra, are strikingly absent from that of
the H II layer (e.g. the Orion Bar and the M17SW interface,
Tenorio-Tagle et al. 1982; Beltrametti et al. 1982; Rozyczka
1985). In this scenario, the HII regions are “hollow”. One
interesting possibility is that gas photo-evaporating from dense
condensations exposed to ionized radiation, creates a gas
mass input within the cavity sufficient to balance the outward
flow of matter. Are the shells reflecting such a mass input? To
show that this is a plausible interpretation, one must quan-
tify the mass input, as well as the dust properties and excita-
tion conditions, required to match the shells brightness and
its distinct mid-IR colors.

So far most of the studies on the mid-IR properties of
these HII regions and smaller bubbles have been phe-
nomenological and looking into the spatial distribution of the
different emission components and not their physics. A small
bubble where a more quantitative analysis has been carried
out is G28.82-0.23 (aka N49) is nearly axis-symmetric, excited by a
single OSV star, which has a thick 8 µm shell surrounding at 24 µm a diffuse bubble (see e.g. [Watson et al. 2008, Fig. 7],

Everett & Churchwell (2010) proposed a model where the
mid-IR emission of G28.82-0.23 arises from dust entrained by the stellar wind. This interpretation involves a hot (∼10^5
K), high pressure plama (p/k ∼ 10^5 K cm^-3) where dust life-
time is shorter than the expansion timescale. It requires that
dust is constantly replenished by photo-evaporation of high
density (10^4 cm^-3) dusty gas clouds that have been overrun by the expanding nebula. Collisional excitation by hot elec-
trons contribute significantly to the heating of dust. Infrared
dust emission is the dominant cooling channel of the dusty
wind, which reduces the energy available for wind-driven ex-

Section 3 describes the morphology of M16 based on IR photo-
graphs and radiation pressure from their central OB stars (e.g.

section 4 and 5 we present exhaustive modeling of the dust
properties. We first model the dust SEDs with UV heating
only, and this sets constraints on the radiation field intensity
and dust size distribution. Then we consider the possibility that
the shell emission arises from a hot plasma where dust would be heated by collisions with electrons. The reader not
interested in the details of the modeling can skip sections 4
and 5. In section 6, we propose two scenarios of the present
evolutionary state of the Eagle Nebula, which could account
for the mid-IR shell and fit within present observational
constraints. The paper results are summarized in section 7.

2. Observations

The Eagle Nebula has recently been observed by the Spitzer
Space Telescope as part of the GLIMPSE (program #00146,
Benjamin et al. 2003) and MIPS/GAL (program #205976,
Carey et al. 2009) inner Galaxy surveys. The GLIMPSE survey
has made use of the Infrared Array Camera (IRAC, Fazio et al.
2004), while MIPS/GAL has been realized with the Multiband
Imaging Photometer for Spitzer (MIPS, Rieke et al. 2004). In
both cases we have used their enhanced products (Squires et al.
2005). The MIPS/GAL 24 µm data has been complemented with
archival observations (Spitzer program #20726) and reprocessed
using the standard Post-Basic Calibrated Data tool. A
three-color image combining IRAC and MIPS data is shown on
figure 1.

Most of the data processing performed on the MIPS/GAL
24 µm observations is described in Mizuno et al. (2008) and
Carey et al. (2009). At 70 µm, Spitzer detectors are Ge:Ga pho-
tocconductors. When observing bright, structured emission, like
the one in the Eagle Nebula, such detectors show significant
variations in responsivity, which manifest themselves as visible
stripes in the final images, and result in photometric errors of
several tens of percent. This effect has required an offline
reprocessing of the data, with tools specifically designed to, at
the same time, reconstruct the history-dependent responsivity
variations of the detectors and mitigate the associated stripes.
The photometric uncertainty of extended emission is lowered from about 50% on the brightest features down to about 15%
on the enhanced MIPS 70 µm data. The specific pipeline del-
voped for the MIPS/GAL 70 µm observations will be detailed in

We complete the Spitzer observations of M16 with previous
IR survey from MSX and observations from ISO, both photo-

1 http://ssc.spitzer.caltech.edu/postbcd/
Fig. 1. Composite Spitzer color image combining the IRAC 5.8 μm (blue) bands with MIPS 24 (green) and 70 μm (red). The FOV is ~ 30’. N is up and E is left. The two black boxes outline the Pillars of Creation, which raise from the bottom to the center, pointing slightly to the West and the Spire, on the East, almost pointing straight toward the West. The position and spectral type of the most massive stars of NGC6611 is overplot: O stars are in red, B stars are in white.

3. Observational results

We use the many IR observations available to create a portrait of the nebula from NIR to FIR wavelengths. We then perform aperture measurements on both the broad band images and spectroscopic observations in order to get characteristic spectral energy distributions (SEDs) and spectra of the Eagle Nebula. We focus our comments on the two main features of the nebula: the PDRs and the inner shell.

3.1. Images

The three-color image of Fig. 1 clearly highlights differences between intermediate wavelengths on the one side (MIPS24 in green) and the shorter and longer wavelengths on the other side (IRAC8 in red and MIPS70 in blue). The whole molecular cloud appears in purple while the inner shell is green.

- At wavelengths shorter than ~ 10 μm, IRAC, MSX and ISO observations show the molecular cloud surface heated by the cluster UV radiation. The Pillars of Creation, the Spire (see Fig. 1 to identify these structures) and less contrasted emission extend towards the cluster from the North and the East. To the NW and the SE, the rim of an outer shell can be identified. It corresponds to the edge of the Eagle Nebula as seen in Hα.
- At intermediate wavelengths, between ~ 12 and 24 μm, MSX, ISO and MIPS observations exhibit a significantly dis-
features like the tip of the main Pillar and Pilbratt’s blob. Rather than linearly interpolate the missing pixels like it has been done previously on ISOCAM/CVF data (e.g. [Urquhart et al. 2003]), we use these data as is. We present and interpret spectroscopic and photometric measurements separately.

3.2. Spectroscopic measurements

We compute average spectra on multiple positions within the Pillars of Creation area covered by the ISOCAM/CVF data. We use square boxes of 4x4 pixels (24x24"on ISOCAM/CVF 6"pixel field of view) to estimate the mean brightness of several features. We use this method for both “ON” and “OFF” positions. We combine three different OFF positions to build a unique OFF spectrum. The resulting ON-OFF spectra are shown on figure 2 for two positions within the main Pillar of Creation and one on Pilbratt’s blob. These three positions, marked on figure 2(d), correspond respectively to spectra D, B and A of figure 2 from [Urquhart et al. 2003]. One of our OFF positions is close to their spectrum C. As a consequence, our results are similar to theirs:

- The spectra of the Pillars of Creation (see Fig. 2(b) and 2(c)) exhibit the characteristics of PDRs spectra with strong PAH features and gas lines. They also present the Si absorption feature around 10 μm. There are some variations between the two positions, mainly regarding PAH features and gas lines strength, which traces variations in the excitation conditions between these two positions within the column of gas and dust.
- The spectrum of Pilbratt’s blob (see Fig. 2(a)) exhibits a strong continuum with very weak gas lines and PAHs bands. We thus assume, as a first approximation, that the MIPS 24 μm shell is dust continuum dominated.
- The OFF position has a spectrum with a weaker continuum than the blob but stronger than the Pillars. It also has much weaker lines and features than within the gaseous and dusty columns.

3.2.2. Photometric measurements

We combine IR observations of the Eagle Nebula from three different observatory: MSX, ISO and Spitzer. Therefore, we first lower the spatial resolution of each observations to that of MSX data (20′). Then, as we did with the spectroscopic measurements, we pick up several interesting and contrasted features within the nebula. We name them as follows. The “PDR” group of features contains the tip of the main Pillar of Creation (“Pillar”, also known as Column I, with an embedded source at its tip, see Fig. 3(a)), the tip of the Spire (“Spire”, also known as Column IV, with an embedded source at its tip, see Fig. 4(a)), the tip of the Spire (“Spire”, also known as Column IV, with an embedded source at its tip, see Fig. 4(a)), and a PDR within the main Pillar of Creation (“Shoulder”, see Fig. 5(a)). The “Shell” group of features contains Pilbratt’s blob (“Blob”, see Fig. 6(a)), the contrasted border of the main shell (“Shell border”, see Fig. 7(a)), a diffuse shell that extends towards the opposite direction (“Reverse shell”, see Fig. 8(a)), a bright filament on the North-West side of the nebula (“Filament”, see Fig. 9(a)) and some more diffuse emission on the South-West side of the nebula (“Diffuse”, see Fig. 10(a)). For each structure, the main difficulty of the measurement is to properly estimate the background emission behind each of them. This is particularly true for the MIPS 70 μm images.

We illustrate our method on the example of Pilbratt’s blob but it is mainly valid for the whole set of structures. We first

2 http://www.spitzer.caltech.edu/ Media/releases/ssc2008-11/ssc2008-11a.shtml

Fig. 2. ISOCAM/CVF mean spectra observed (a) on Pilbratt’s blob, (b) at the tip of the main Pillar of Creation and (c) within the Pillar of Creations. Dotted lines are ON spectra, dashed lines are OFF spectra, thick solid lines are ON-OFF spectra. OFF and ON positions are shown on the ISOCAM/CVF 3′ by 3′ field of view, here at the wavelength of 12 μm. North is up, East to the left.

The IR morphology of the Eagle Nebula is common among other star forming regions. Churchwell et al. (2006) have listed many such “bubbles” across the entire GLIMPSE Galactic plane survey with IRAC. Combining GLIMPSE and MIPS GAL 24 μm surveys reveals an inner shell for most of these regions.
Fig. 3. (a) Three color image as in figure 1 with the region along which the profiles are measured for the main Pillar of Creation. (b) Normalized infrared emission profiles (MIPS70 in red, MIPS24 in green and IRAC8 in blue, solid lines) and interpolations performed to measure the fluxes of the structure (dashed lines).

Fig. 4. Same as figure 6 for the position of the “Spire”. select a rectangular area that encompasses the blob, as shown on Fig. 6(a). We choose the orientation of the selected area in such a way we avoid to select other neighboring contrasted features (e.g. the Pillars of Creation). We then compute the mean profile of the blob and its surrounding by averaging all the pixels along the short axis. The resulting normalized profiles for Pilbratt’s

Fig. 5. Same as figure 6 for the position of the “Shoulder”.

Fig. 6. Same as figure 6 for the position of the “Blob”. select a rectangular area that encompasses the blob, as shown on Fig. 6(a). We choose the orientation of the selected area in such a way we avoid to select other neighboring contrasted features (e.g. the Pillars of Creation). We then compute the mean profile of the blob and its surrounding by averaging all the pixels along the short axis. The resulting normalized profiles for Pilbratt’s
Fig. 7. Same as figure 6 for the position of the “Shell Border”. The darker sections of the profiles show the top and bottom of the “jump” used to measure the fluxes at each wavelength.

Fig. 8. Same as figure 6 for the position of the “Reverse Shell”. The blob are shown on Fig. 6(b) for several wavelengths. The profiles for the other features are shown on Fig. 7(b) to 10(b).

Fig. 9. Same as figure 6 for the position of the “Filament”.

Fig. 10. Same as figure 6 for the position of the “Diffuse”.

We then measure the mid to far-IR SED of each structure. We adapt the method as a function of the profile shape. For the structures that present a peak of emission at every wavelength (e.g. Pilbratt’s blob, Spire), we estimate the background through a spline interpolation of the profile on both sides of the peak.
(see Fig. 5(b)). The flux of the structure is thus given by the integration of the background subtracted profile over the size of the structure. The actual size over which we integrate the flux may slightly vary from one channel to another. The uncertainty on each measurement is given by the range of background values as estimated by the spline interpolation. For the other structures, where the profiles exhibit a “jump” (case of the shell border, see Fig. 7(b)), we estimate the height of the “jump” at each wavelength by measuring the difference of the surface brightness between the top and bottom of the “jump”. The uncertainty on each measurement is given by the standard deviation of the surface brightness at the top and the bottom of the “jump”.

While the measurements are usually straightforward on the MIPS 24 µm profiles, they are significantly more uncertain on the MIPS 70 µm profiles, especially for less contrasted structures like the “Filament” or the “Diffuse” emission. In those two last cases, we are not sure about the exact spatial extent of the structure at 70 µm and the range over which to estimate the background (see Fig. 10(b)). This generally also applies to the IRAC 8 and 6 µm measurements, but to a lesser extent. In particular, for the “Filament” structure, the discrepancy in the profile’s peak position between MIPS 24 µm and MIPS 70 µm or IRAC 8 µm is significant enough so we do not consider them as probing the same physical conditions (see Fig. 9(b) and 10(b)). Since there is no other obvious feature at the position of the MIPS 24 µm peak, we will thus use the MIPS70 µm measurement as an upper limit. Additionally, the uncertainty on the MIPS 70 µm flux of the “Diffuse” is significantly higher. The resulting photometric SEDs, normalized to MIPS 24 µm, are presented on figure 11. Again, the differences between the structures within the shell and those within the PDRs are clear.

- The PDRs of M16, both at the tip of the Spire and within the Pillars of Creation, are characterized by an almost flat SED from near to mid infrared and a continuous increase mid to far infrared wavelengths. The SEDs of the position with an embedded source (“Pillar” and “Spire”) do not appear to be different from that of the “Shoulder” at near infrared wavelengths. At longer wavelengths, the SED of the “Shoulder” increases slightly less than those of the “Pillar” and the “Spire”, which encompass embedded source. The ratio between MIPS24 and MIPS70 is about 0.1 for the “Shoulder” and about 0.3 at the tip of the main Pillar of Creation and the Spire.
- The inside shell, at Pilbratt’s blob position and on bright contrasted structures, is characterized by a significantly steeper increase of the intensity from near to mid infrared and a flat or decreasing SED from mid to far infrared. On Pilbratt’s blob, the Shell border and the Reverse shell, the MIPS24 to MIPS 70 ratio is about 4.5, 2.3 and 0.95 respectively.
- The Filament and the Diffuse SEDs appear in between these two sets of SEDs. Both their MIPS24 to MIPS 70 ratio is lower than inside the shell and their near to mid infrared SED is steeper than within PDRs but the uncertainties are significantly larger. As a consequence, in the following sections, we do not discuss these last two positions.

The measurements of the near-IR to far-IR SEDs confirm what spectroscopic observations were suggesting: the dust within the inner shell is significantly different from that within PDRs. The addition of the MIPS 70 µm and its comparison to MIPS 24 µm provide us with constraints on the position of the dust emission peak in the FIR. We explore in the next section whether the difference arises from external excitation or intrinsic properties.

4. UV heating of the dust

In this section, we model the dust emission within M16 using the dust model of Compiègne et al. (2011).

4.1. Method

The dust model of Compiègne et al. (2011) is an updated version of the original of Desert et al. (1990) model. In their model, Compiègne et al. (2011) use four dust components: (1) polycyclic aromatic hydrocarbons (PAH), (2) stochastically heated very small grains of amorphous carbon (VSG or SamC), (3) large amorphous carbon grains (LaM) and (4) amorphous silicates (aSi). We combine LamC and aSi grains into a unique big grains (BG) component using these grains relative abundances found in the diffuse high galactic latitude (DHGL) medium (Compiègne et al. 2011). We assume a fix dust-to-gas mass ratio of 1%. We then use the dust model to compute the emission spectra of the three dust components (PAHs, VSGs and BGs) illuminated by the incident radiation field from the star cluster NGC6611.

We used the STARBURST99 online model3 described in Leitherer et al. (1999) and Vázquez & Leitherer (2005) to define the spectral shape of the radiation field from the illuminating star cluster NGC6611. We use the following parameters: 2 millions years old cluster, Salpeter initial mass function ($dn/dM \propto M^{-2.35}$), stellar masses from 1 $M_\odot$ to 100 $M_\odot$. The modeled radiation field corresponds to 1.6 $\times 10^3 L_\odot$. We normalize it so that it is in agreement with the total flux of the most massive stars of the cluster. Dufour et al. (2006a) have presented an analysis of VLT-FLAMES spectroscopy for NGC6611. Their online catalogue (Dufour et al. 2006b) lists stars classified as earlier than B9. The 42 members of NGC6611 have a combined total luminosity of $3.4 \times 10^6 L_\odot$, which is a factor 480 smaller than

3 http://www.stsci.edu/science/starburst99/
the Starburst99 model output spectrum. We apply that correction factor to the model spectrum of the ISRF. In Habing units – integrated intensity of the solar neighborhood from 912 to 2000 Å or $1.6 \times 10^{-3}$ erg s$^{-1}$ cm$^{-2}$ – the cluster radiation field intensity is $\chi_0 \approx 4800$ at a distance of 3 parsecs (see section 4.3 for a discussion on the spatial variations of the ISRF). In the following, we use this value as a reference for the dust model.

For the features within the shell (“Blob”, “Shell border” and “Reverse shell”), the use of a non-attenuated radiation field is acceptable since the UV optical depth is low. For the features within the PDRs (“Pillar”, “Spire” and “Shoulder”), we have to take into account the extinction of the ISRF by the ionized layer of gas and the PDR layer itself. We model this in a simple way by removing the Lyman continuum photons and with a far-UV extinction of 1 magnitude. Such an extinction accounts for the fact that the emission from PDRs comes from a range of depths into UV-dark clouds with a weighting proportional to the UV field. A more detailed study of the PDRs is beyond the scope of this paper.

4.2. MIPS 24 µm to MIPS 70 µm ratio as a tracer of $\chi$

We first use the dust model of Compiègne et al. (2011) to compute the MIPS 24 µm to MIPS 70 µm ratio of the dust emission for different dust size distributions to show how it is related to $\chi$. Within this wavelength range, the PAH contributions to the emission is weak relative to that of VSGs and BGs. Therefore, we present the MIPS 24 µm to MIPS 70 µm ratio as a function of $\chi$ for three size distributions: VSGs only, BGs only and a mixture of VSGs and BGs that matches their relative abundance in the diffuse high Galactic latitude medium (DHGL, Compiègne et al. 2011). Therefore, we take into account any dust evolutionary process that would destroy a specific grain size component. Figure 12 shows the results along with the MIPS 24 µm to MIPS 70 µm ratio measured for the Eagle Nebula structures, both within the shell and the PDRs. The differences between the set of curves for the PDRs and that for the shell are not significant. We first make no distinction while presenting them. Then we discuss the results for the PDRs and Shell structures independently.

For a given $\chi/\chi_0$, VSGs always have a higher MIPS24/MIPS70 as they are hotter than BGs. However, for $\chi/\chi_0 \gtrsim 1.0$, MIPS24/MIPS70 is almost independent, within a factor of a few, from the dust size distribution. These values of $\chi$ correspond to the large values of the MIPS24/MIPS70 (> 1). For $\chi/\chi_0 \lesssim 1.0$, MIPS24/MIPS70 is significantly more dependent on the grain size distribution with difference up to almost 2 orders of magnitude. Likewise, for a given MIPS24/MIPS70, the required $\chi/\chi_0$ is always higher for BGs than VSGs. The difference is as small as a factor of a few for high values of MIPS24/MIPS70 and as high as almost 2 orders of magnitude for low values of MIPS24/MIPS70. Therefore, given MIPS24/MIPS70, the constraint on the intensity of the ISRF is stronger for higher values of $\chi$ and requires a better knowledge of the dust size distribution (e.g. as provided by other IR observations, see next subsection) at low values of $\chi$.

On the contrary, constraining the dust size distribution requires an a priori on $\chi$ and can better be done at low values of $\chi$.

According to the model, the PDR structures (“Pillar”, “Spire” and “Shoulder”) require an ISRF intensity at most a factor 2 lower than the reference, and no lower limit can be estimated because we have no constraint on the dust size distribution. However, if we assume it does not significantly depart from that of the DHGL medium, the MIPS24 to MIPS70 ratio within PDRs are best interpreted with $\chi/\chi_{ISRF0} \approx 0.1$. The inner shell structures (“Blob”, “Shell border” and “Reverse shell”) are more on the high end of the ISRF intensity. The “Shell border” and the “Blob” are best interpreted with $\chi/\chi_{ISRF0}$ of at least a few and up to 16, whether the dust size distribution is dominated by BGs or VSGs. The difference between the ISRF intensity that illuminates these two structures and the PDRs is thus at least an order of magnitude. The “Reverse shell” position however is not strongly constrained and overlaps those of the PDR structures. If at this position the dust size distribution is determined by VSGs, then $\chi/\chi_{ISRF0} \approx 0.1$ while $\chi/\chi_{ISRF0} \sim 1$ if the BGs contribute the most to the dust size distribution. The full range of required ISRF intensities for each structure is given in Table 1.

Table 1. Lower and upper limits of $\chi/\chi_0$ for the whole set of structures as deduced from their MIPS 24 µm to MIPS 70 µm ratio.

| Shell structure   | $\chi/\chi_0$ | PDR structure | $\chi/\chi_0$ |
|-------------------|---------------|---------------|---------------|
| Reverse shell     | 0.13-1.3      | Pillar        | < 0.3         |
| Blob              | 5.6-16        | Shoulder      | < 0.6         |
| Shell border      | 1.4-5.4       | Spire         | < 0.4         |

Indirectly the MIPS 24 µm to MIPS 70 µm ratio also provides us with a measurement of the equilibrium dust temperature $T_{eq}$ of the largest dust particles. In figure 13 we plot the BGs equilibrium temperature, provided by the dust model, as a function of $\chi$, for both the PDR and the Shell structures, and for both types of large grains used in the model of Compiègne et al. (2011): LamC and aSil. For a given radiation field intensity $\chi/\chi_{ISRF0}$, we plot the upper and lower limits for the equilibrium temperatures of each grain type. The difference between both type of BG components is not really significant. In figure 13 we hatch the range of equilibrium temperatures for the values of $\chi/\chi_0$ given by Fig. 12. 0.13 < $\chi/\chi_0$ < 16 for the Shell and $\chi/\chi_0$ < 0.6 for the PDR structures. While the smallest LamC grains in the PDR structures may reach equilibrium temperature as high as 71 K, those are in limited number. Likewise, only the largest grains in the Shell structures may reach equilibrium temperature as low as 24 K. The majority of the grains, as traced by the most abundant size bin of each BG component (also plotted in figure 13), span a range of equilibrium temperatures that does not overlap significantly between the Shell and the PDR structures. For the PDR structures, equilibrium temperatures for the most abundant size $20 < T_{eq} < 50$ K while for the inner shell structures $35$ K < $T_{eq}$ < 100 K. Therefore, equilibrium temperatures above 50 K can only be efficiently reached by BGs in the inner shell while equilibrium temperatures below 50 K are mostly found in the PDRs. The dust in the inner shell is thus significantly hotter than that in the PDRs. Indebetouw et al. (2007) have used IRAS 60 µm to IRAS 100 µm ratio to build a low spatial resolution (4.3’) color temperature map of the dust in M16. Their values range from 32 K in the molecular cloud to 40 K inside the nebula. We build the same map (not shown here) using IRAS 25 µm to IRAS 60 µm ratio (to better match the MIPS24 to MIPS 70 µm diagnostic) and find color temperature ranging from 45 K to 65 K, more in agreement with our measurements of the BGs equilibrium temperature in the shell. The remaining difference may come from the lower spatial resolution that averages “hot” features with “cold” features within the beam.
Fig. 12. MIPS 24 $\mu$m to MIPS 70 $\mu$m ratio as a function of the ISRF intensity, as predicted by the model of Compiègne et al. (2011). Several dust size distribution are used: (dotted line) BGs only, (dashed-line) VSGs only and (solid line) mix of BGs and VSGs. The MIPS24-to-MIPS70 ratio for several structures within M16 is indicated. The ISRF spectral shape is that mention in the text with (a) no extinction, (b) A(FUV) = 1 mag and the Lyman continuum photons removed.

Fig. 13. BGs equilibrium temperature as a function of the ISRF intensity. The hatched area corresponds to the range of equilibrium temperatures span by the entire BGs size distribution. The solid lines represent the equilibrium temperature for the most abundant size bin. The hatched area and the solid line are only plotted for the values of $\chi/\chi_0$ that are given by figure 12. Black is for LamC grains, red is for aSil grains as described in Compiègne et al. (2011). The ISRF spectral shape is that mention in the text with (a) no extinction, (b) A(FUV) = 1 mag and the Lyman continuum photons removed.

Table 2. Best-fit parameters for SEDs of the Eagle Nebula. The ISRF intensity, the dust size distribution, in terms of relative mass ratio abundances, and the total dust column density are given. The parameters for the diffuse high Galactic latitude (DHGL) reference of Compiègne et al. (2011) are also given. The dust-to-gas mass ratio is fixed at 0.01 therefore a dust mass column density of $1.7 \mu g.cm^{-2}$ corresponds to $10^{20} H.cm^{-2}$.

| Position       | $\chi/\chi_0$ | $Y_{BG}(M/H)$ | $Y_{VSG}(M/H)$ | $Y_{BG}(M/H)$ | $\sigma_{dust}(\mu g.cm^{-2})$ |
|----------------|---------------|---------------|---------------|---------------|-------------------------------|
| DHGL           | 7.8 x 10^{-4} | 1.65 x 10^{-4} | 9.25 x 10^{-3} | 1.7           |
| Pillar         | 0.19 ± 0.04   | (2.64 ± 0.57) x 10^{-4} | (2.45 ± 0.90) x 10^{-4} | (9.49 ± 1.82) x 10^{-3} | 380 |
| Shoulder       | 0.43 ± 0.08   | (2.51 ± 0.45) x 10^{-4} | (1.12 ± 0.95) x 10^{-4} | (9.64 ± 2.15) x 10^{-3} | 33  |
| Spine          | 0.12 ± 0.05   | (2.95 ± 1.27) x 10^{-4} | (5.09 ± 2.89) x 10^{-4} | (9.20 ± 3.62) x 10^{-3} | 870 |
| Shell border   | 4.436 ± 1.03  | (4.85 ± 1.12) x 10^{-4} | (3.69 ± 2.71) x 10^{-4} | (9.63 ± 2.77) x 10^{-3} | 0.2  |
| Blob           | 0.969 ± 2.33  | (5.98 ± 3.07) x 10^{-4} | (9.40 ± 1.82) x 10^{-3} | 2.9  |
| Reverse shell  | 1.15 ± 0.13   | (1.99 ± 0.31) x 10^{-3} | (8.01 ± 0.23) x 10^{-3} | 2.1  |
| Shell Border   | 2*            | (6.68 ± 4.47) x 10^{-3} | (1.50 ± 0.77) x 10^{-2} | (3.59 ± 2.29) x 10^{-3} | 0.17 |

$\sigma_{dust}$ ($VSG$) = 5.5 nm
which corresponds to a gas column density of a few $10^{22}$ cm$^{-2}$ or a visual extinction of a few magnitudes, significantly larger than that required for attenuating the incident UV radiation field. The three “PDR” positions give very similar results, especially in terms of PAH abundance which varies by less than 10%. The VSG abundance is varying more significantly, up to a factor 5. The BG always dominates the dust size distribution with abundance very close to that of the DHGL.

The positions within the “Shell” require larger values of $\chi/\chi_0$ (about a few) in agreement with values from Table 1, a significant depletion of the PAHs and a significant increase of the VSG abundance, up to a factor 10, with respect to the PDRs values and at the expense of the BG component. The total dust column density is about $10^{-6}$ g/cm$^2$, similar to DHGL values and which corresponds to a gas column density of about $10^{20}$ cm$^{-2}$. As a consequence of the increased $\chi$, the VSG and BG emission spectra peak at very close wavelengths (see Fig. 14(f)). We show in the previous section that MIPS24 to MIPS70 ratios are available while only MIPS 70 measurement is available at wavelengths longer than the peak position. The fit process is thus biased very close to that of the DHGL.

The positions within the “Shell” require larger values of $\chi/\chi_0$ (about a few) in agreement with values from Table 1, a significant depletion of the PAHs and a significant increase of the VSG abundance, up to a factor 10, with respect to the PDRs values and at the expense of the BG component. The total dust column density is about $10^{-6}$ g/cm$^2$, similar to DHGL values and which corresponds to a gas column density of about $10^{20}$ cm$^{-2}$. As a consequence of the increased $\chi$, the VSG and BG emission spectra peak at very close wavelengths (see Fig. 14(f)). We show in the previous section that MIPS24 to MIPS70 ratios are available while only MIPS 70 measurement is available at wavelengths longer than the peak position. The fit process is thus biased very close to that of the DHGL.
give results that are very similar to each other and very different from those of the PDRs positions: (1) an incident radiation field intensity a factor of a few larger than that provided by the star cluster NGC6611 and about an order of magnitude larger than that required for the PDR positions, (2) a significant depletion of the PAHs and (3) an increase of the VSGs abundance relative to BGs as compared to the PDRs positions.

In order to explore furthermore the importance of a change in the dust size distribution, we redo the fit of the “Shell border” with a fixed intensity of the radiation field $\chi/\chi_0 = 2$ and a free mean size of the VSG component ($a_0$). In the model of Compiegne et al. (2011) for the DHGL medium, the VSGs size distribution is assumed to have a log-normal distribution (with the centre radius $a_0 = 2$ nm and the width of the distribution $\sigma = 0.35$ nm). We keep the width of the log-normal distribution constant and set free the centre size $a_0$ between 0.6 and 20 nm. The other free parameters for that fit are the abundances of the dust components, as previously. The best-fit is plotted in Figure 15 and the parameters are given in Table 2. A significant increase of the mean size of the VSGs, by almost a factor 3, is required. There are almost no PAHs, as in the previous fits. The BGs are about a factor 3 less abundant than in the previous fit and about a factor 30 less abundant than in the DHGL. The abundance of VSGs is about 60 times higher than in the DHGL medium, though the uncertainty remains large (~75%). Therefore, the “Shell border” SED requires that most of the dust mass is concentrated into the VSGs component. Despite those variations of the dust size distribution, the total dust column density remains very similar to that of the fit with a fixed mean size for VSGs ($0.17\ \mu g\ cm^{-2}$). We also try the same fit with $\chi/\chi_0 = 1$ but find that the uncertainties on the parameters are then significantly higher (>100%).

We conclude that the MIR shell SED can either be accounted for a significant change in the dust size distribution or by an additional source of heating besides the star cluster radiation field. In the following, we first discuss two sources of UV heating that may account for the values of $\chi/\chi_0 > 1$ required to fit the “Shell” SEDs. The first one is related to the spatial variations of $\chi$ due to the exact positions of the OB stars in the sky. The second originates in the Lyman $\alpha$ photons emitted by the hydrogen and absorbed by the dust grains. We then consider, in the next section, another heating process originating from collisions with the gas.

### 4.4. Spatial variations of the incident radiation field

Depending on the exact positions of the main OB stars of NGC6611 within the Eagle Nebula, the local incident radiation field intensity may vary and thus explain the required values of $\chi/\chi_0$. For the “cold” PDRs features, it is easy to explain values of $\chi/\chi_0 < 1$ as the stars are not all together on the plane of the sky, additionally to probable shadow effects already mentioned. However, the required values of $\chi/\chi_0 > 1$ for the “Shell” structures cannot be accounted for by the same interpretation. In Figure 11, we indicate the position and the spectral type of the members of NGC6611, according to Dufton et al. (2006a). We compute the variations of the ISRF intensity $\chi_0$ as a function of the position, taking into account the luminosity and position of each individual member of the cluster. We assume that all the stars and the “Shell” structures are in the same plane of the sky. Therefore, the values of the local ISRF intensity we compute are thus upper-limits and the corrected values of $\chi/\chi_0$ required for the best-fits are lower-limits. All these values are reported in Table 3. The corrections factors are about a factor of a few at most. The required values of $\chi/\chi_0$ for the Shell Border and the Blob are still at least a factor 2 to 3 higher than that provided by the star cluster.

The position of the members of NGC6611 also reveals that Pilbratt’s Blob is very close to an 08.5V star, as shown on Fig. 16. This suggests a possible local action of the winds from this star. The shock provided by the winds may account for a local enhancement of the density within the shell and possibly for dust processing. The same interpretation does not hold for the “Shell border” and the “Reverse shell” position which both

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**Table 3.** Correction factors on $\chi_0$ from the dispersion of the stars in the sky plane and corrected $\chi/\chi_0$ required for the best-fits.

| Position       | Correction factor | Corrected $\chi/\chi_0$ (best fit) |
|----------------|-------------------|-------------------------------------|
| Shell border   | < 1.3             | > 2.9                               |
| Blob           | < 4.5             | > 2.1                               |
| Reverse shell  | < 6.8             | > 0.2                               |
are away from any OB star, as also shown in Fig. [16] We discuss collisional heating in section 5.

4.5. Lyman alpha photons heating

We show here that Lyman $\alpha$ photons are not a significant heat source for the shell. Every Lyman $\alpha$ photons emitted by an hydrogen atom, after multiple absorption and reemission by other hydrogen atoms, either succeed to escape the medium or is absorbed by a dust grain. The Lyman $\alpha$ contribution to the dust IR brightness is $S_{\lambda\alpha} = \frac{n_e \times n_H \times a_2 \times h_{\lambda\alpha} \times d_{l}}{E_{\lambda} \times a_2 \times h_{\lambda\alpha}}$, where $E_{\lambda}$ is the emission measure and $a_2$ the hydrogen recombination coefficient to levels 2 and higher. The equation assumes that all recombinations from excited levels produce a Ly$\alpha$ photon that is absorbed by dust.

We compute the EM from Br observations of M16 obtained at the Canada-France-Hawaii Telescope (CFHT). These observations will be presented in a future paper. They do not show a counterpart of the “Blob”. but there is an increase of the Br emission associated with “Shell border” of $E_{\lambda} = 3.5 \times 10^5$ pc.cm$^{-6}$. The Ly$\alpha$ photons total flux that we estimate from these measurements is $S_{\lambda\alpha} = 0.048$ erg.s$^{-1}$.cm$^{-2}$. In comparison, the 24 $\mu$m brightness of the “Shell border” is 230 MJy/sec which corresponds to a bolometric intensity of 0.37 erg.s$^{-1}$.cm$^{-2}$ that we measure on the best fit (see Fig. 7(b)) between 1 and 1000 $\mu$m. The extra heating provided by the Ly$\alpha$ photons is thus about a factor 8 too small.

5. Collisional heating of dust

In this section, we face the difficulty of explaining the shell infrared colors with UV heating by considering the possibility that gas-grains collisions provide additional dust heating. We quantify the conditions that would be required to fit the shell SED with a combination of radiative+collisional heating of dust.

We use the work of Dwek (1987) to quantify the heat deposited in the grain by collisions with electrons as a function of grain size and plasma temperature. Like in section 4 we use the DUSTEM model with a combination of silicates and amorphous carbon grains (Compiègne et al. 2011). Since the DUSTEM code does not include collisional excitation, we wrote a specific module to compute the distribution of grain temperatures for stochastic heating by both photons and collisions. This code takes into account the Maxwellian distribution of the electrons kinetic energy. The results of our calculations are illustrated in Fig. [17] for carbon grains. The Spitzer colors $I_{\lambda}(8\mu m)/I_{\lambda}(24\mu m)$ and $I_{\lambda}(24\mu m)/I_{\lambda}(70\mu m)$ are plotted versus grain size for radiative heating by the mean Eagle Nebula radiation field, and radiative+collisional heating for a range of electron densities $n_e$. The temperature of the electrons $T_e$ is fixed to $10^6$ K. Our specific choice of $T_e$ is not critical, because the colors depend mainly on the plasma pressure, i.e. the product $n_e \times T_e$. Collisional heating has a significant impact on the infrared colors for pressures $p/k$ larger than a few $10^{-1}$ K.cm$^{-3}$. The figure shows that both colors may fit be pressures $p/k = 1.9 \times 10^{-1}$ K.cm$^{-3}$ and a characteristic grain size of $\sim 10$ nm. For this plasma pressure, collisions with electrons dominate the heating of small grains with radii $< 10$ nm, while radiation is the main heating source for larger grains. To illustrate the ability of the dust model to fit the shell SED, we use a dust size distribution that combines a log-normal size distribution for very small carbon grains plus a power-law size distribution for silicates. We keep the relative fractions of dust mass in carbon grains and silicates to their interstellar values: 1/3 and 2/3, respectively. In Fig. [18] we show a fit of the “Shell border” SED obtained for $n_e = 30$ cm$^{-3}$ and $T_e = 10^4$ K. For this fit, the characteristic radius (i.e. the mean value of the log-normal size distribution) of the carbon VSGs is 6.5 nm. This value is somewhat smaller than the value that may be inferred from Fig. [17] because the silicates contribute to about half of the 70 $\mu$m flux. The figure shows that for a given plasma temperature the characteristic grain size is tightly constrained by the ($I_{\lambda}(8\mu m)/I_{\lambda}(24\mu m)$) ratio. It depends on the plasma temperature because this constraint is related to the stochastic heating of the smallest grains by collisions with electrons. The model also allows us to estimate the dust mass in the shell. The dust surface density is $2 \times 10^{-8}$ M$_\odot$pc$^{-2}$. Scaling this value by the full extent of the shell (4 pc radius), we find a total dust mass of $3 \times 10^{-7}$ M$_\odot$.

The pressure inferred from the modeling of the collisional heating may be compared with independent constraints on the pressure within the Eagle nebula. This comparison raises difficulties with, but does not fully rule out, the collisional heating solution. The gas pressure inferred from Hubble observations optical line emission from the faint end of the photo-evaporation flows arising from Pillar I is $p/k \sim 10^7$ K.cm$^{-3}$ (see Fig. 7b, absicssa 0 in Hester et al. 1996). This value sets an upper limit on the ambient pressure around the flows, which is lower than the pressure required for the collisional heating solution. One possible way out of this problem is that Pillar I is not embedded in the shell. The shell pressure can also be estimated from Pilbratt’s blob. The blob is close to an O8.5V star known to be associated with the ionizing cluster of the Eagle Nebula (see Fig. 15). Its morphology and position on one side of the star suggests that it traces a bow shock created by a supersonic motion between the shell and the star (van Buren et al. 1999). If this interpretation is right, it sets a constraint on the shell pressure. At the standoff distance $d_o$, i.e. the distance between the star and the edge of the blob, there is a pressure equilibrium between the wind pressure and the ambient pressure plus the ram pressure associated with the star motion. Hence, the wind pressure at the standoff distance, $p_w = M_w \times V_w / (4 \pi \times d_o^2)$, is an upper limit on the ambient pressure. From the 24$\mu$m image, $d_o = 0.2$ pc. We use the empirical relation between wind momentum and stellar luminosity (Kudritzki & Puls 2000) for an O8.5V star $M_w \times V_w \sim 2 \times 10^{-7}$ M$_\odot$yr$^{-1} \times 10^3$ km.s$^{-1}$. Hence, we find $p_w/k = 2 \times 10^9$ K.cm$^{-3}$, a value more than one order of magnitude smaller than the pressure required for the collisional heating solution. Here, the plausible way out would be that Pilbratt’s blob is not a bow-shock.

6. The nature of the mid-IR shell

In this final part of the paper, we discuss the results from our dust modeling in the context of the Eagle Nebula massive star forming region. We have shown in the previous sections that the dust SED of the MIR shell cannot be accounted for by standard models (i.e. interstellar dust heated by UV radiation). We find two possible explanations. (1) The fraction of the dust mass in stochastically heated VSGs is much larger in the shell than in the diffuse interstellar medium. (2) There is an additional source of heating which could be collisional heating in a high pressure plasma. Here we present two sceneri that can explain either or both of these requirements. In the first one the mid-IR shell is a windblown shell, where the dust is heated by UV photons and where large grains have been grown into stochastically heated small particles. In the second scenari we investigate a more speculative hypothesis
higher than the average pressure in the interstellar medium. The shell matter moves outward, because the wind pressure is sure and a fixed temperature show the impact of collisional heating for a range of plasma pres-
tions and exposed to ionizing radiation from the stellar cluster,

In this first scenario, matter outflowing from dense condensa-
tions and exposed to ionizing radiation from the stellar cluster, in particular the Eagle pillars, supply the shell with a continuous
inflow of gas and dust. The mechanical pressure from the stellar
winds push this matter outward, but the shell persists provided
that its outward expansion is compensated by continuing photo-
evaporation. Since the shell is within the ionizing boundary of
the Nebula, the diffuse matter in the shell is fully ionized. The
gas density and column density are too small to absorb all of the
ionizing radiation. To quantify this scenario, we apply the em-
pirical relation between wind momentum and stellar luminosity
(Kudritzki & Puls 2000) to each of the O stars in the cluster. For
a wind velocity of 2500 km s$^{-1}$ (Kudritzki & Puls 2000), the
mechanical energy injection is $\sim$ 2500 L$_{\odot}$, a factor 20 smaller
than the shell luminosity $\sim$ 5 $\times$ 10$^{4}$ L$_{\odot}$ as estimated from the
shell brightness $B_{IR}$ and its angular diameter (14”). Unlike what
Everett & Churchwell (2010) advocated for N49, in M16 the shell
IR emission cannot be powered by the stellar winds, and
does not represent a major cooling channel that impacts the dy-
amical evolution of a wind-blown shell.

The shell must originates from the only available source of
dust, i.e., evaporating dense gas condensations within the
ionization boundary of the Nebula. The difficulty in being certain that this is the right interpretation comes from inter-
stellar dust (see sections 4 and 5). Indeed, our dust modeling in
section 4 shows that the shell SED cannot be fit with the
standard interstellar dust size distribution. The fits shown in
Figure 14(d) and 15 illustrate the uncertainty of the model-
ing. It is beyond the scope of this paper to explore in a sys-
tematic way the full range of possible solutions, but we are
confident that any fit will involve shattering of dust grains to
nanometric sizes.

As a consequence of such an interpretation for the Eagle Nebula shell, we conclude that massive star forming regions have a major impact on carbon dust. Galliano et al. (2003) reached a similar conclusion in their modeling of the infrared
SED of the dwarf, star forming, galaxy NGC 1569. Observations of the ionized gas kinematics do provide evidence for supersonic velocities in the immediate environment of pillars in star forming
regions (Westmoquette et al., 2009). Hence, the grinding of the
carbon dust could be the result of grain shattering in grain-grain
collisions within shocks driven by the dynamical interaction be-
tween the stellar winds and the shell. Theoretical modeling of
the dust dynamics in shocks suggest that this is a plausible hy-
pothesis (Jones, 2004). Guillet et al., (2009) have quantified dust

Fig. 17. Spitzer colors I$_{(8\mu m)}/I_{(24\mu m)}$ and $I_{(24\mu m)}/I_{(70\mu m)}$
for carbon grains versus grain size. The solid line gives the colors
for radiative heating for the Eagle Nebula ISRF. The other lines
show the impact of collisional heating for a range of plasma pres-

Fig. 18. Fit the spectral energy distribution measured on the
Eagle shell with radiative plus collisional heating. The ISRF is
that determined in section 4 with $\chi/\chi_0 = 1$. The electron density
is 30 cm$^{-3}$ and the plasma temperature 10$^6$ K.

where the shell would be a supernova remnant that would be
cooling through IR dust emission.

6.1. A wind blown shell

In this first scenario, matter outflowing from dense condensa-
tions and exposed to ionizing radiation from the stellar cluster, in
particular the Eagle pillars, supply the shell with a continuous
inflow of gas and dust. The mechanical pressure from the stellar
winds push this matter outward, but the shell persists provided
that its outward expansion is compensated by continuing photo-
evaporation. Since the shell is within the ionizing boundary of
the nebula, the diffuse matter in the shell is fully ionized. The
gas density and column density are too small to absorb all of the
ionizing radiation. To quantify this scenario, we apply the em-
pirical relation between wind momentum and stellar luminosity
(Kudritzki & Puls 2000) to each of the O stars in the cluster. For
a shell inner radius of 3 pc, we find that the winds pressure
$p_{winds}/k = 5 \times 10^5$ K cm$^{-3}$. This value is a few times larger than the radiation pressure estimated from the shell infrared bright-
ness $p_{rad}/k \sim B_{IR}/c \sim 10^3$ K cm$^{-3}$, where $B_{IR}$ is the mean bolo-
metric IR brightness $\sim 0.4$ erg cm$^{-2}$s$^{-1}$ and $c$ the speed of light.
The shell matter moves outward, because the wind pressure is
higher than the average pressure in the interstellar medium. The
expansion velocity is commensurate with the sound speed in the
shell, and thus must be $\sim 10$ km s$^{-1}$. Since the shell is a few par-
secs wide, the shell matter needs to be renewed over a timescale
of a few $10^3$ yr by on-going photo-evaporation.

In the Eagle Nebula, the pressure from stellar winds is too
low to account for the shell colors with collisional excitation (see
section 5 for details). The mechanical power from the winds is
also too small to contribute to the IR luminosity from the shell.
For a wind velocity of 2500 km s$^{-1}$ (Kudritzki & Puls 2000), the
mechanical energy injection is $\sim$ 2500 L$_{\odot}$, a factor 20 smaller
than the shell luminosity $\sim 5 \times 10^4$ L$_{\odot}$ as estimated from the
shell brightness $B_{IR}$ and its angular diameter (14”).
processing by the passage of J-shocks of a few 10 km.s⁻¹. They find that the mass fraction in the largest grains is reduced to the profit of the smallest, as a result of grain shattering and dust vaporization.

6.2. A supernova remnant

Alternatively, we keep the usual distribution of dust grain sizes, but look for another source of pressure: a supernova remnant. This is not unexpected for a 3-Myr old nebula with very massive stars (M* ~ 80M⊙; Hillenbrand et al. 1993). If so, we would be witnessing a specific time in the evolution of the remnant where the plasma pressure and temperature would be such that the remnant cools through dust emission. This scenario relates directly to the fit of the shell SED quantified in section 5.

The infrared dust emission from fast shocks driven by supernovae has been quantified in several theoretical papers (e.g. Draine 1981; Dwek et al. 1994). Overall, dust is found to be a significant but not dominant coolant of shocked plasma due to dust destruction. For a dust to hydrogen mass ratio of 1% and a Solar metallicity, dust cooling is larger than atomic cooling for temperatures > 5 × 10⁴ K, but, for temperatures T larger than ~ 10⁸ K, the dust destruction timescale by sputtering is smaller than the gas cooling time (Smith et al. 1996; Guillard et al. 2009). This framework has been used to interpret observations of young remnants starting from the first infrared detections of supernovae with the IRAS survey (Dwek, 1987). We propose here a distinct idea, where the shell infrared emission seen towards the Eagle Nebula would be related to the late evolution of a remnant.

For the model shown in Fig. 18, 1/3 of the shell infrared emission is powered by grain collisions with electrons and contributes to the plasma cooling. The remaining 2/3 is provided by radiative heating of the dust. Assuming that the dust infrared emission is the dominant gas cooling channel, the isobaric cooling time of the infrared emitting plasma is \( t_{\text{cool}} = \frac{\pi}{2} \times 2.3 \times k T_{\text{G}} / (\Gamma \times m_p \times x_{\text{dust}}) \) where \( \Gamma \) is the collisional heating rate per unit dust mass, \( m_p \) the proton mass and \( x_{\text{dust}} \) the dust to hydrogen mass ratio. With the \( \Gamma \) value derived from the fit in Fig. 18, we find \( t_{\text{cool}} = 1500 \times (x_{\text{dust}}/0.01)^{−1} \) yr. The dust-to-hydrogen mass ratio \( x_{\text{dust}} \) is not constrained by the modeling. This factor may well be smaller than the reference value of 1% due to dust destruction by sputtering. The SED fit also allows us to estimate the plasma column density and thereby the internal energy \( U \) of the infrared emitting plasma. The model gives \( N_{\text{H}} = 8 \times 10^{18} \times (x_{\text{dust}}/0.01)^{−1} \) H.cm⁻². From there we find \( U \geq 2 \times 10^{48} \times (x_{\text{dust}}/0.01)^{−1} \) erg. This value is a small fraction of the expansion energy associated with a typical supernova explosion (~ 10⁵¹ erg). Within our remnant hypothesis, this difference indicates that the cooling time is short and that only a small fraction of the shocked plasma is contributing to the infrared emission. One possibility to account for this fact would be that we are observing the late evolution of the remnant when the low density hot plasma heated to high temperatures early in the expansion of the remnant is cooling through turbulent mixing with photo-ionized gas (Begelman & Fabian 1990). This plasma would have a long intrinsic cooling timescale, because its dust would have been destroyed early in the evolution of the remnant. For a pressure of \( p/k = 5 \times 10^7 \) K.cm⁻³, the cooling timescale through atomic processes of a dust-free plasma at a temperature of 10⁷ K is 2 × 10⁵ yr.

This interpretation will need to be tested against additional observations. The absence of bright diffuse emission in the Chandra X-ray images (Linsky et al. 2007) can possibly be accounted for. For instance, the hot plasma may be too tenuous to be seen in emission, while the X-ray emission from the turbulent mixing layers would be soft and thus heavily attenuated by foreground gas. We re-analyzed the Chandra ACIS-I observations of M16 (Linsky et al. 2007) to search for a faint background emission. After removal of point sources, we do find residual X-ray emission over the SW section of the mid-IR shell where the foreground extinction is the lowest. The emission spectrum fit gives \( kT \) in the range 0.6 – 2 keV and a foreground column density within 2.45×10²² H.cm⁻². The absorption corrected X-ray brightness is \( 1.3 \times 10^{-15} \) erg.s⁻¹.cm⁻².s⁻¹. If this emission arises from the mid-IR shell (i.e. from a sightline length ~ 10 pc), we derive a plasma pressure \( p/k \sim 10^8 \) K.cm⁻³. This result does not allow us to conclude that the X-ray emission arises from a supernova remnant, but, if it does, the X-ray emission is consistent with the dust being collisionally excited in a high pressure plasma. In this case, if the X-ray emission fills the mid-IR cavity, the shell X-ray luminosity would be \( \sim 10^{33} \) erg.s⁻¹. This is on the low side for an SNR: for comparison, the W28 SNR, which is interacting with a molecular cloud, has a total X-ray luminosity \( L_X \sim 6 \times 10^{34} \) erg.s⁻¹ (Rho & Borkowski 2002). However, our value of \( L_X \) for the putative M16 SNR is a lower limit, since it does not take into account the soft X-ray emission from cooler gas that is more heavily absorbed. Further X-ray observations are planned to clarify this point. MIR spectroscopic maps of M16 with Spitzer, covering a wide range of emission features and ionization energies, will provide an additional test to be investigated.

7. Conclusions

- We present new IR images of the Eagle Nebula from the MIPSGAL survey that reveal the well-known illuminated clouds of dust and gas. The MIPS 24 µm observations show the same inner shell-like feature as mid-infrared observations from ISO or MSX. It is significantly brighter than the PDRs. Relative to these previous observations, the MIPSGAL survey has the advantage to also probe the far infrared emission of the dust. The structure of the nebula as seen in the MIPS 70 µm observations is close to that of the shorter wavelengths as seen in the GLIMPSE survey (from 3 to 8 µm): the cloud surface is significantly brighter than the inner shell.

- Thanks to the MIPS 24 and MIPS 70 µm observations, we are able to give constraints on the temperature of the grains emitting in the FIR range and the required interstellar radiation field intensity to heat them up to these temperatures with our dust model. The dust temperature varies from ~35 K in the PDRs to ~70 K in the shell. The required intensity of the ISRF within the PDRs is about an order of magnitude lower than that provided by the star cluster NGC6611. The shell of hot dust, however, requires an ISRF intensity about a factor of a few higher than that provided by the cluster.

- Combining all the IR observations at our disposal into SEDs that sample the whole nebula with our dust model, we fit the observations to constrain both the radiation field intensity and the dust size distribution. In the PDRs, we confirm the required ISRF intensity is about a few tenths of that provided by NGC6611. The dust size distribution is dominated by BGs even though all the dust components are present with abundance a factor of a few, at most, different from those of the DHGL medium. In the shell, we also confirm the required ISRF intensity is a factor of a few larger than that
of NGC6611. The PAHs are absent and the VSGs are more abundant, up to a factor 10, than in the DHGL medium.

- Extinction and the dispersion of the stars across the nebula can account for the lower ISRF intensity required for the PDRs. On the contrary, an additional source of heating is required for the shell. Neither the spatial variations of the ISRF intensity nor the Lyman alpha photons contribution can account for the discrepancy between required and provided UV heating of the dust. Exact positions of the stars reveal that Pilbratt’s blob is only 0.25 pc from an O8.5V star and may thus be a bow shock.

- We then invoke gas-grain collisions as an extra source of heating. Our modeling leads to a fit of the shell SED that requires a pressure of a few $10^3$ K cm$^{-3}$. Such a pressure is at least at a factor of a few larger than that inferred either from optical observations at the end of the photo-evaporation flow arising from Pillar or from Pilbratt’s blob bow shock nature.

- We finally discuss two interpretations of the mid-IR shell in the general context of a massive star forming region. In a first scenario, we propose that the shell is wind blown by the stars. We find that the star cluster does not provide enough mechanical energy via stellar winds to power the shell emission. Therefore the shell is explained by a modified dust grain size distribution (large carbon grains shattered to nanometric sizes) with heating only due to UV emission. The implication is then that massive star forming regions like M16 have a major impact on their dust size distribution: this can be checked on other similar regions. Alternatively, we propose a second scenario, in which the shell is heated by the hidden remnant of a supernova from a very massive progenitor, and for which the dust provides a fast cooling. The implication is then that our observations occur during a short-lived, late stage of evolution of the remnant: this can be checked with new X-ray observations.

The Eagle Nebula IR emission morphology is similar to that of many other star forming regions observed within the GLIMPSE and MIPS GAL surveys [Churchwell et al. 2003, Carey et al. 2009]. For the first time, it is quantitatively discussed in terms of dust modeling. The work we present would need to be extended to other SFRs with IR morphology similar to that of M16 to ascertain whether the interpretation would be challenged by the same problem in accounting for the dust temperature. Moreover, future analysis of additional observations (mid-to-far IR spectral mapping from Spitzer/IRS and MIPS-SED, near-IR narrow band imaging from CFHT/WIRCam) of the Eagle Nebula will provide us with more constraints on the physical conditions and dust properties in M16’s inner shell.

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