The Eagle Nebula unveiled by the MIPSGAL survey

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ABSTRACT

We report the discovery of structured diffuse infrared emission in MIPSGAL 24 μm Spitzer images of the Eagle Nebula that fills the wind-blown cavity of this massive star forming region. We combine the Spitzer data with ISO and MSX observations to present a spectral energy distribution of this emission. The SED peaks at 24 μm and is fit by emission from silicates and/or graphite grains at ~90 K. We show that the emission cannot be powered by the NGC 6611 cluster radiation or winds. The spatial extent, the dust temperature and the infrared brightness can all be accounted for by collisional heating of interstellar dust swept by a supernova explosion.

Subject headings: galaxies: ISM — infrared: galaxies — infrared: ISM — ISM: dust, extinction — ISM: structure

1. Introduction

The Eagle Nebula (M16) is one of the closest star formation region in our Galaxy and one of the most well-studied. This HII region lies a distance of ~2kpc from the Earth (Hillenbrand et al. 1993) and has become famous thanks to its molecular pillars imaged more than ten years ago by the *Hubble Space Telescope* (Hester et al. 1996). These "elephant trunks" are a few arcminutes long (a few parsecs) and are the results of the interaction between the intense radiation field from the nearby clusters of about 20 OB stars (NGC 6611) and the molecular cloud out of which they are formed. The so-called "Pillars of Creation" shade a triggered generation of star formation within their tip.

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The *Infrared Space Observatory* (ISO) had imaged the Eagle Nebula both with photometric and spectroscopic instruments, from 5 to 15 μm (Pilbratt et al. 1998; Omont et al. 2003; Urquhart et al. 2003). These observations have revealed structures whose emission spectra exhibit significant differences from the pillars. The lack of longer wavelengths data, now available with the *Spitzer Space Telescope* (SST), prevent previous studies to interpret those observations. We have analyzed the complete pool of infrared data at our disposal in order to characterize the dust grains properties within the Eagle Nebula.

2. Observations

The Eagle Nebula has been observed by the SST as part of the GLIMPSE and MIPSGAL inner Galaxy surveys (Benjamin et al. 2003; Carey et al. 2008, programs P00146 and P20597 respectively). In both cases we have used their enhanced products. The 24 μm data has been complemented with archival observations (program P20726) and reprocessed using the SST Post-Basic Calibrated Data tools. The GLIMPSE survey has made use of the InfraRed Array Camera

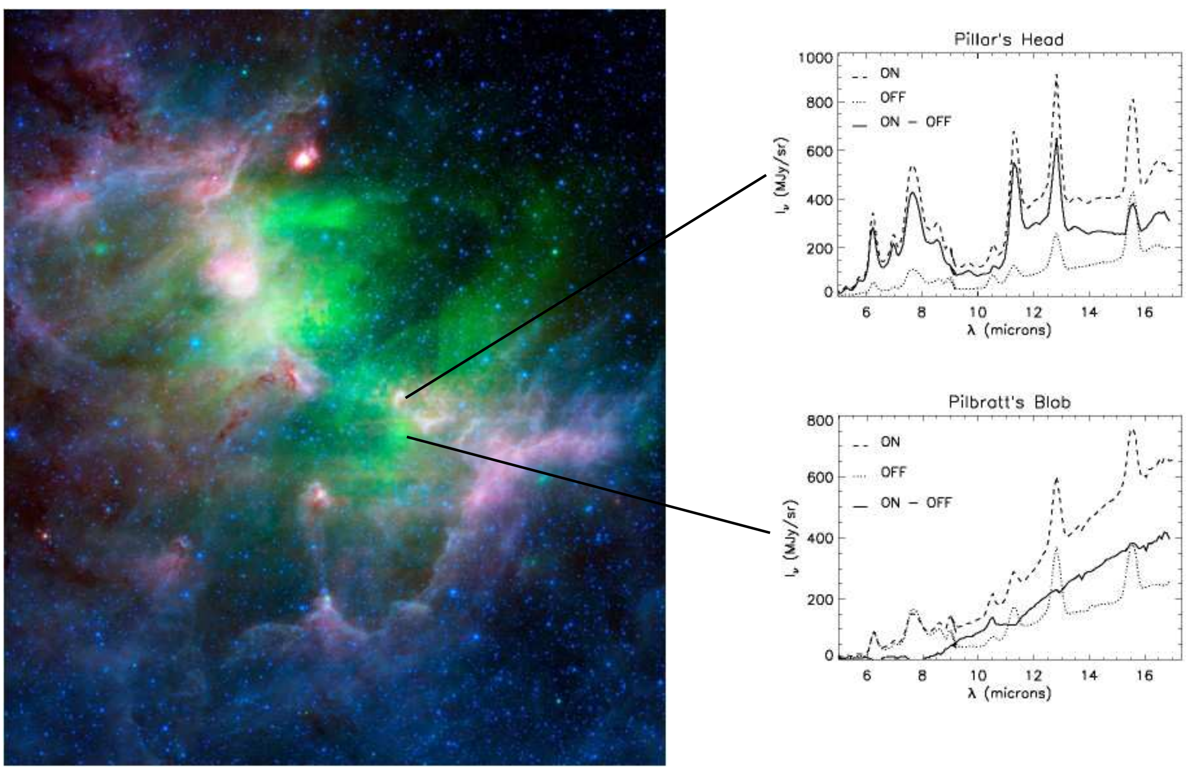

Fig. 1.— *Left:* composite of IRAC and MIPS. Blue is 4.5 and 8.0 μm, green is 24 μm and red is 70 μm. *Right:* ISOCAM/CVF spectroscopic observations of the PIllars and Pilbratt's blob.

(IRAC, Fazio et al. 2004) while the MIPSGAL one of the Multiband Imaging Photometer for Spitzer (MIPS, Rieke et al. 2004). A three-color image combining IRAC and MIPS data is shown on Fig. 1. We have added to these data previous ISO and MSX observations of the Nebula. The infrared broad band images reveal:

- at wavelengths shorter than ~ 10 μm, IRAC, MSX and ISO, as well as MIPS 70 μm observations show the molecular cloud surface heated by the cluster UV radiation: the pillars and less contrasted emission extending towards the cluster from the North and the East. To the NW and the SE, the rim of an outer shell, which corresponds to the edge of the nebula as seen in Hα, can be identified.
- at intermediary wavelengths, between ~ 12 and 24 μm, MSX, ISO and MIPS 24 μm have a distinct morphology with a shell filling the cavity in between the pillars. The shell extends over 12' in the NW-SE direction towards the pillars and further out to the SW where there is no emission either at shorter or longer wavelength. Some bright features within the shell have already been identified by ISO (e.g. Pilbratt's blob, to the East of the main pillar). The lack of far-infrared observations prevented previous authors to conclude anything specific on its nature.

Spectroscopic observations from ISO are available on a small area (3'x3') around the top of the Pillars of Creation. They cover the Pilbratt's blob structure. Spectroscopic ON - OFF measurements (see Fig. 1) reveal:

- the Pillars exhibit strong PAH features and gas lines that are commonly observed within photo-dominated regions (PDRs).
- Pilbratt's blob exhibits a strong continuum with very weak gas lines and PAHs bands.

A complete spectral energy distribution of the shell from NIR to FIR is shown on figure 2.

3. MIPS 24/70 ratio and grains temperature

The lack of IFR observations prevent previous studies to understand the properties of the dust within the shell. The availability of MIPS 70 μm provides us with a way to constrain the temperature of the larger grains. We have measured the ratio between MIPS 24 μm and MIPS 70 μm within the Eagle Nebula, both on the Pillars of Creation and within the inner shell, by performing aperture photometry. We have also measured this ratio the same way on various "bubbles" across the Galactic plane (Churchwell et al. 2006). We finally complete the comparison sample with KAO observations of Orion nebula (Werner et al. 1976) and M17a (Gatley et al. 1979) as well as a sample of ultra-compact HII regions (UCHII) from Wood & Churchwell (1989) and SST observations of Cassiopeia A supernovae remnant (SNR).

Within the Pillars of Creation, the MIPS 24 to MIPS 70 ratio is about 0.2, a value in agreement with PDR/HII regions mixture within other Galactic plane bubbles, UCHII and nebulae. The corresponding dust grain temperature is thus about 50-70 K for an emissivity in ν^2 or ν.

Within the shell, on several brightness peaks, the MIPS 24 to MIPS 70 ratio is about 1.3 to 1.5. This ratio is not found within other Galactic bubbles, UCHII or nebulae. The only regions where the MIPS 24 to MIPS 70 ratio close or higher than those values are SNRs. The dust grain temperature is thus about 80-100 K.

4. Modeling of the spectral energy distributions

We use our dust model (updated version of Désert et al. 1990) to quantify the stellar radiation field required to power the infrared shell dust. The spectral shape of the incident radiation field has been approximated by the synthetic spectrum of a young (2 Myr) cluster of massive stars using the Starburst99 stellar synthesis model, for a Salpeter IMF and a 100 $M_\odot$ upper mass cut-off

For the Pillars of Creation, we find that the intensity of the required stellar radiation field is about 2000 in Habing unit (units of the Solar Neighborhood far-UV eld: 1.6×10^{-3}erg.s^{-1}.cm^{-2} integrated from 912 to 2000 Å). This value is in good agreement with the one deduced from the combination of the 24 most massive stars of the illuminating cluster. For the shell, we find that the required intensity is about 20,000 or one order of magnitude higher than that provided by the cluster. The best fit provided by our dust model is obtained with almost no PAHs (see Fig. 2). Even if we take into account variations in the dust size distribution between the shell and the pillars, we

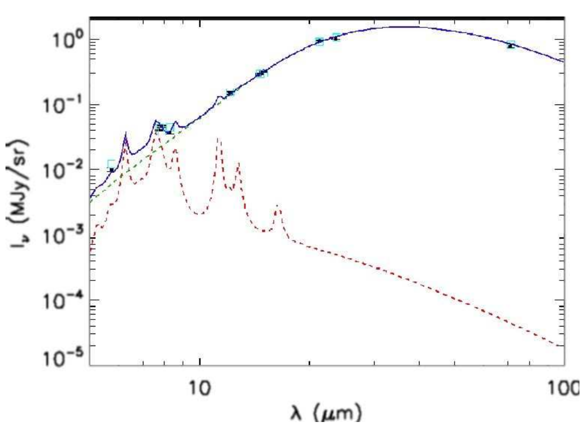

Fig. 2.— Complete spectral energy distribution of a bright structure within the shell and its adjustment by our dust model.

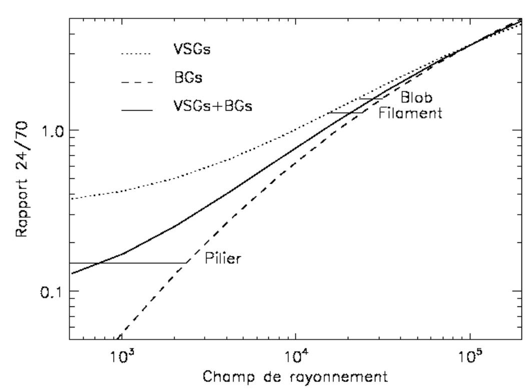

Fig. 3.— MIPS24 to MIPS70 ratio as a function of the interstellar radiation field for various dust size distribution.

cannot explain the radiation field discrepancy (see Fig. 3).

We thus face the following question: what may account for such a difference between the cluster luminosity and the required energy to power the shell ?

4.1. Radiative heating

Lyman α photons are an additional source of dust heating in HII gas. For Pilbratt's blob, the emission measure of 10^4 pc.cm^{-6} leads to an infrared brightness of 0.16 erg.s^{-1}.cm^{-2} or 7% of the blob total infrared brightness. Their contribution is thus not really significant here.

The shell luminosity is only a few percent of the cluster luminosity and the mechanical to radiative luminosity ratio provided by Starbust99 models is about a few 10^{-3}. The optically thin shell, which reprocesses only a small fraction of the cluster radiation, thus cannot be excited by the UV photons produced in wind driven shocks.

4.2. Collisional heating

Faced with the difficulty of explaining the shell FIR color with UV heating, we quantified the required conditions for dust excitation by gas-grain collisions. We used the work of Dwek (1987)

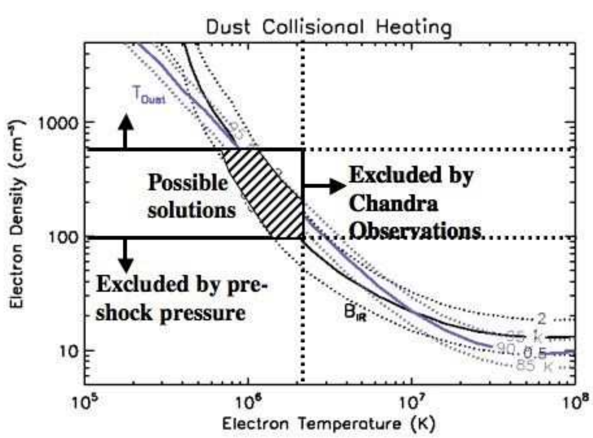

Fig. 4.— Electronic densities and temperatures for which the dust heating is provided by grain-electron collisions.

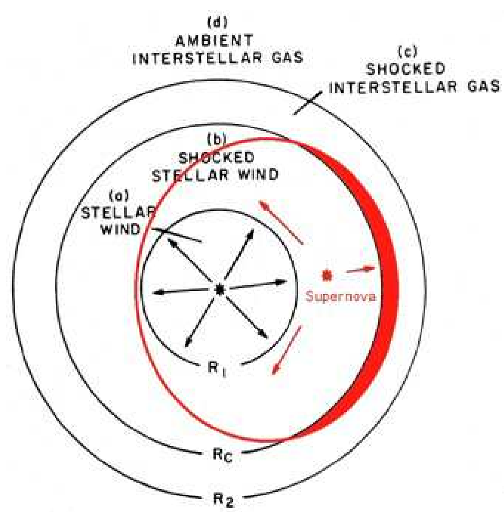

Fig. 5.— Proposed scenario of a SNR that occurs within the star forming region where the progenitor was born.

to compute the set of electronic densities and temperatures for which the dust heating is provided by grain-electron collisions (see Fig. 4). The resulting plasma pressure is about 10^9 K.cm^{-3}. Shock heated gas observed within wind blown cavities of luminous star forming regions (M17 and Rosette Nebula, Townsley et al. 2003) is at a pressure of a few 10^6 K.cm^{-3}, too low to account for the Eagle shell dust temperature. According to the volume of this shell, its estimated thermal energy is about 10^{51} erg, which corresponds to the kinetic energy released by a supernova explosion.

5. The supernova remnant interpretation

The scenario we propose is illustrated by figure 5. Since massive stars live for a few million years, they may explode into supernova (SN) within the star forming region where they were born. The SN ejecta freely expand in a low density cavity previously emptied by the cluster UV radiation and winds. Then they plow into a shell of photo-ionized gas, forming a shock front that is strongly radiative. The shock illuminates a dust wall, heating the grains to MIR temperatures.

5.1. Shell cooling through dust emission

According to the shock velocity, given by the post-shock electronic temperature, and taking into account the required conditions for collisional heating, the full power radiated by the shocked gas is about 2.5 erg.s^{-1}.cm^{-2} for $10^6 \leq T_e \leq 10^7$ K. This value is comparable to Pilbratt's blob infrared brightness. The supernova interpretation thus requires the gas cooling time to be smaller than the supernova age. This leads us to a condition on the pre-shock density: $n \geq 20$ cm^{-3} for an electronic temperature $T_e \leq 3 \times 10^6$ K and a dust-to-gas mass ratio $x_d \geq 5 \times 10^{-3}$. The age of the supernova would then be about 4000 years.

5.2. X-rays and radio observations

Known SNRs have all been identified in X-rays and/or radio observations. It is then natural to ask why the infrared shell has not been discovered earlier at those wavelengths. The absence of conspicuous X-ray and radio counterpart may be a corollary to the high IR brightness of the shell and be interpreted within our scenario.

The non-thermal radio emission may be weak because the cavity density is very low. As a consequence, there is no shock within the cavity that may accelerate the electron.

The X-ray emission is soft because the gas density is high within the photo-ionized gas that evaporates out of the molecular clouds. Moreover, it could have been hidden by the foreground extinction ($A_V \sim 10$, Indebetouw et al. 2007)

6. Summary

The recent MIPSGAL observations of the Eagle Nebula provide us with a more accurate view of the inner shell of dust previously discovered by ISO. The availability of FIR data gives us the first opportunity to measure the dust temperature. This measurement leads us to a discrepancy between the required luminosity and that provided by the cluster. We then evoke gas-grain collisions to heat the dust and propose that a supernova is the source of the amount of energy required to power such a volume.

If confirmed by further observations (accepted at the CFHT and VLT), this interpretation is opening additional perspectives. (1) The Eagle SNR would be the first one identified in the infrared through dust emission. It provides criteria to look for other SNRs in massive star forming regions missed in X-rays and radio. (2) It offers a striking illustration of the impact of infrared emission on the energetics of SN occurring in dusty environments. The reduction of the cooling time affects their dynamics and their feedback on the interstellar matter. (3) In the MIR images, the shell encompasses the Pillars of Creation. The explosion center might be offset but the SN interpretation raises the question of a possible interaction: could the pillars have been shaped by the blast wave? (4) The SN interpretation is an additional link between the Eagle Nebula and the early history of the Solar system where decay products of radioactive elements produced in a supernova are found.

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