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KEYS TO SPITZER OBSERVATIONS OF LUMINOUS STAR FORMING REGIONS

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RESUMEN

Observaciones del telescopio espacial Spitzer están abriendo una nueva perspectiva sobre la formación de estrellas masivas en la Galaxia, galaxias cercanas y galaxias infrarrojas. Presentamos resultados de un análisis de observaciones Spitzer de 30 Dorado junto con imágenes H_2 1-0 S(1)and Brγ y espectroscopía infrarroja obtenidas con ISO. Hemos relacionado la distribución espacial y espectral de la emisión infrarroja, con el impacto radiativo y dinámico del super cúmulo estelar R136 sobre la estructura del medio interestelar y la composición del polvo. Este análisis da claves para interpretar las imágenes Spitzer de regiones de formación de estrellas masivas y abre perspectivas sobre el impacto de cúmulos estelares de alta masa en el medio interestelar.

ABSTRACT

Spitzer Space Telescope observations are opening a new perspective on massive star formation in the Galaxy, nearby galaxies and luminous infrared galaxies. We summarize results from an analysis of 30 Doradus Spitzer observations together with near infrared H_2 1-0 S(1)and Brγ images and spectro-imaging observations obtained with ISO. We relate the spatial and spectral distribution of the 30 Doradus mid-infrared emission to the radiative and dynamical impact of the R136 super star cluster on the ISM structure and dust composition. This analysis provides keys to the interpretation of mid-IR observations of massive star forming regions and insight on massive clusters pre-supernova feedback on their environment.

Key Words: **H II REGIONS — ISM: DUST — ISM: MOLECULAR CLOUDS — STARS: FORMATION**

1. INTRODUCTION

Stars are born in dusty clouds. In their early evolution they escape direct detection at UV and visible wavelengths because their light is absorbed by dust. After the IRAS all-sky survey and the Infrared Space Observatory (ISO), the Spitzer Space Telescope is allowing us to image and take spectra of the dust infrared emission with unprecedented sensitivity and angular resolution. These observations reveal early stages of star formation on a wide range of scales and distances from single low mass stars in nearby star forming regions to embedded super star clusters in distant luminous galaxies. A major outcome of these observations is the continuing discovery of star-burst galaxies referred to as infrared galaxies because their infrared luminosity tracing recent star formation is higher than their visible luminosity. Star formation rates in these galaxies are inferred to be one to a few orders of magnitude higher than in the Galaxy. Observations suggest that these galaxies are powered by Super Star Clusters (SSCs) containing hundreds to thousands of OB stars (Whitmore et al. 1999). It is still unclear how SSCs form and thereby how star formation in infrared galaxies works. A major open question is how massive star formation can be locally so efficient despite the disruptive impact of massive stars on their environment (Tan and McKee 2001). But the action of massive stars is also known to trigger formation of new stars and may thus also play a positive role in the formation of massive clusters.

In the LMC, at the center of 30 Doradus, the most luminous star forming region in the local Group, lies the nearest example of an SSC (R136) with an age of 1-3 $\times$ 10^6yrs, $L_* = 10^8\,L_\odot$ and $M_* = 5 \times 10^4\,M_\odot$. R136 is a small SSC but the only one for which present observations permit a detailed look at the surrounding interstellar medium. We have analyzed Spitzer images of 30 Doradus together with near infrared H_2 1-0 S(1)and Brγ images and spectro-imaging observations obtained with ISO. This study allows to relate the spatial and spectral distribution of the 30 Doradus mid-infrared emission to the radiative and dynamical impact of the R136 super star cluster on the ISM structure and dust composition (Boulanger et al. 2006). This analysis provides keys to the early (pre-supernova) feedback of SSCs on their environment and of its sig-

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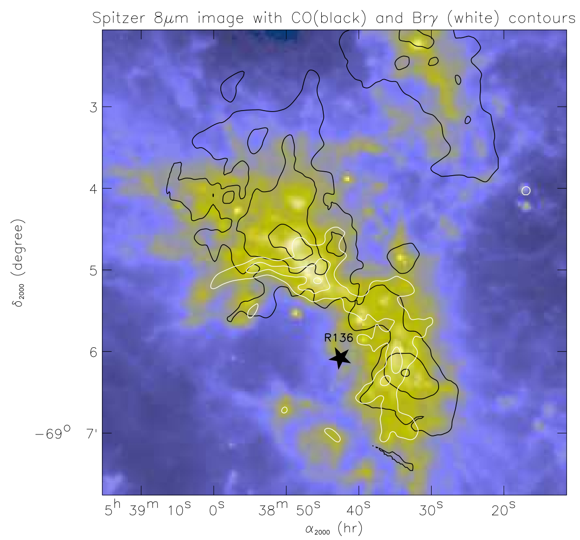

Fig. 1. Spitzer 8μm image of the inner parts of the 30 Doradus nebula with CO(2-1) (black) and Brγ (white) contours. CO observations and Brγ image obtained by Monica Rubio.

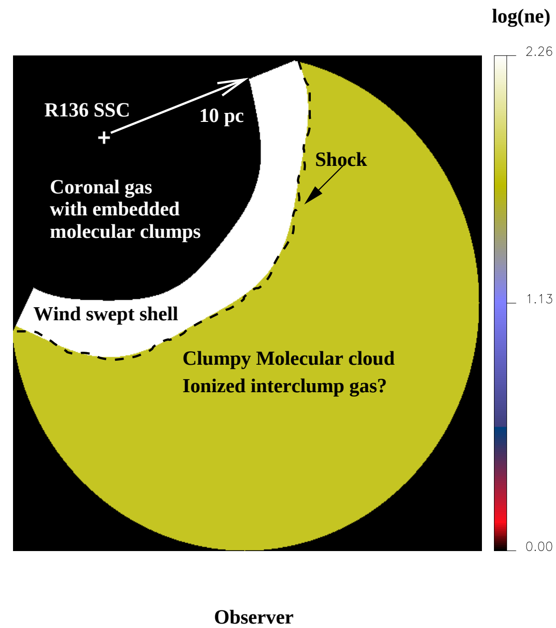

Fig. 2. Schematic cartoon of the interaction between the R136 Super Star Cluster (SSC) and the SW molecular cloud. The drawing represents the distribution of matter along the line of sight and a cut going from R136 to the center of the SW cloud. The observer is to the bottom.

natures in the mid-infrared emission from massive star forming regions.

This paper is organized as follows. In section 2 we discuss the origin of the mid-infrared (mid-IR) emission from massive star forming regions on general grounds. In sections 3 and 4, we summarize results from the Boulanger et al. (2006) analysis of the 30 Doradus data.

2. DIFFUSE MID-IR EMISSION FROM MASSIVE STAR FORMING REGIONS

Images of star forming regions provided by the Spitzer Infrared Array Camera (IRAC) at 3.6, 4.5, 5.9 and 8 μm and the Multi Band Imaging Photometer for Spitzer (MIPS) at 24μm reveal diffuse emission with spectacular structure distinct at the various Spitzer wavelengths (Churchwell et al. 2004). What are these Spitzer images tracing? What can they teach us about the interaction of massive stars with their environment?

To emit at mid-infrared wavelengths dust must be warmer than 100 K. The median dust temperature in galaxies is much smaller, about 20K. In star forming regions the grains are warmer because the stellar radiation field is more intense, but radiation pressure and stellar winds efficiently pushes grains away from luminous stars and large grains equilibrium temperatures are rarely observed to be higher than 100 K. The dust emission invariably peaks in the far-infrared around 100 μm. But dust includes particles small enough to be stochastically heated to temperatures much higher ($\sim$ 1000 K) than the large grains equilibrium temperature by the absorption of single stellar photons (Li and Draine 2001). These particles emit at mid-IR wavelengths down to 3μm. The smallest particles are the carriers of the Polycyclic Aromatic Hydrocarbons (PAHs) mid-IR emission bands. Several of these bands, the 3.3, 6.2, 7.7 and 8.6μm bands fall in the IRAC bands (Flagey et al. 2006). There is also continuum emission associated with very small carbon, possibly silicates, dust grains. At the shortest two wavelengths of IRAC, line and continuum emission from H II gas is also a significant, possibly dominant, interstellar emission.

The IRAC and the MIPS 24μm camera are imaging the emission from PAHs and Very Small Grains (VSGs). A first key to the interpretation of Spitzer images of massive star forming regions 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, (e.g. the Orion Bar Giard et al. 1994 and the M17SW interface Cesarsky et al. 1996) show that PAHs are a main feature of the PDR mid-IR emission spectrum but are strikingly absent from that of the H II layer. PAHs are quickly destroyed when matters flows across the ionization front. Several destruction mechanisms have been proposed: chemisputtering by protons and photo-thermo dissociation and/or Coulomb explosion associated with absorption of high energy photons (Giard et al. 1994). The larger VSGs are present in both the PDR and the H II gas but their mid-IR continuum emission is enhanced in the H II gas by the absorption of the harder Lyman continuum photons.

The spatial distribution/clumpiness of the ionized and molecular gas is a second key underlying the interpretation of the mid-IR emission of massive star forming regions. The surface filling factor of molecular gas fixes the fraction of the stellar radiation which is absorbed in PDRs. The density and dust abundance in the H II gas fixes the fraction of the Lyman continuum absorbed by dust rather than by H and He atoms. Metallicity is an additional factor which affects the ionizing luminosity of massive stars, the UV opacity of interstellar matter and possibly the dust composition and structure of molecular clouds.

In the following two sections, we illustrate this generic discussion with results of our analysis of 30 Doradus observations.

3. INTERSTELLAR MATTER NEAR THE R136 SUPER STAR CLUSTER

Interstellar matter in 30 Doradus has been the topic of many papers over the last decades. The spatial distribution and kinematics of the ionized gas has been analyzed from observations of H recombination lines (e.g. Lazendic et al. 2003, Peck et al. 1997). In Fig. 1 we have zoomed on the two CO clouds at the center of the nebula to the North and South West (SW) of R136. The virial mass of these clouds is $\sim 10^5\, M_\odot$. These clouds share a common radial velocity and are possibly two pieces of a single parent cloud where the cluster was born.

The interaction of R136 with its parent cloud may be understood within the theoretical framework set by McKee et al. (1984) to describe the expansion of photo-ionized wind bubbles in a clumpy medium. We focus on the SW cloud. The main characteristics of our understanding of the R136 interaction with the SW cloud are sketched in Fig. 2. Stellar winds have carved out a cavity within the cloud. The wind blown cavity is filled with hot X-ray emitting gas at a pressure (p/k) of a few $10^6\mathrm{K\,cm^{-3}}$ (Wang 1999).

The winds have bursted out of the molecular clouds in many directions and thereafter expanded out faster in the tenuous surrounding medium creating the outer shells seen in wider images of the nebula. In the direction of the CO clouds (Black contours in Fig. 1), the expansion is still occurring within the clouds. The H II filaments observed at the edge of the two clouds (white contours in Fig. 1) delineate the wind swept shell. The radio recombination line observations of Peck et al. (1997) are the best suited to estimate the expansion velocity of this shell. Taking the molecular cloud velocity as a reference, the wind swept shell seen in direction of R136 is observed to be moving towards us at a velocity of $\sim 20\,\mathrm{km\,s^{-1}}$. Larger velocities are observed for the gas expanding away from us where the wind may have bursted out of the cloud as drawn in Fig. 2.

The CO emission has been interpreted as arising from the shielded interiors of dense clumps with a small (5-10%) surface filling factor (Poglitsch et al. 1995, Pak et al. 1997). The data interpretation presented in these two papers do not set a clear constrain on whether the inter-clump gas is neutral or ionized. At faint levels the $Br\gamma$ emission extends beyond the filaments. This faint emission could arise from the outer surface of the molecular cloud but it may also indicate that the R136 Lyman continuum photons propagate beyond the wind swept shell into the molecular cloud, ionizing the clump surfaces and the inter-clump gas. In the interpretation of the dust observations (Section 4), we favor the latter view.

In a clumpy medium one does expect the ionizing photons to propagate ahead of the wind swept shell in the lower density gas (McKee et al. 1984). A low metallicity does help this to occur because fewer photons are absorbed by dust. The ionization of the inter-clump gas would have raised the pressure at the surface of the clumps, possibly inducing infall. This interpretation of the data opens an interesting insight on contagious star formation that will deserve deeper analysis. The initial conditions for the formation of a massive cluster may be met in the SW 30 Doradus cloud. Evidence for current star formation in this region has been found by Rubio et al. 1998.

4. DUST EVOLUTION

Mid-IR spectro-imaging observations were obtained with ISO over a $3' \times 3'$ field encompassing R136 and the SW molecular cloud. In Boulanger et al. (2006), we found that the PAH emission bands are spatially associated with the H_2 emission and the mid-IR dust continuum with the Brγ emission. We made use of these correlations to separate the contributions from the wind swept H II shell and the molecular cloud to the infrared emission. The Spectral Energy Distributions (SEDs) derived from this correlation analysis are presented in Fig.3. The H II SED is strikingly distinct from that of the SW

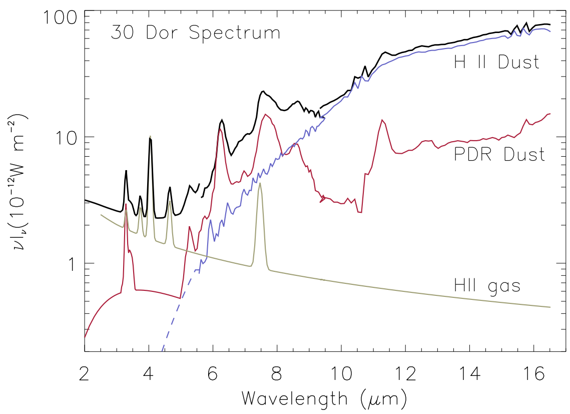

Fig. 3. Global 30 Doradus spectrum (black solid line) obtained by integrating the data over the $3' \times 3'$ CVF field of view with the contribution from the H II gas (light color solid line) and the PDR (grey solid line). The spectra at $\lambda < 5\mu$m are shown with dashed lines because they are inferred from models.

molecular cloud (labeled PDR in the figure). The H II SED rises steeply with increasing wavelengths and shows none of the PAH bands. The H II emission at short wavelengths is dominated by continuum (free-free+free-bound) and line emission from the gas. The difference in dust composition between the PDR and the H II gas is a key to the interpretation of Spitzer mid-IR images of massive star forming regions and the spectra of infrared galaxies. The SW molecular SED is remarkably similar to that of the Galactic archetype PDR NGC 7023 but the continuum is stronger and the bands weaker by a factor 6 for a comparable incoming radiation field (comparable dust excitation). We interpret this result within the molecular cloud picture sketched in Fig. 2. The PAH emission is weak because it is arising from clumps which only fill a small fraction of the ISO beam. The mid-IR continuum represents emission from the PAH-free inter-clump ionized gas.

Measurements of heavy elements in H II gas (e.g. Orion abundances Esteban et al. 2004) show that depletions are comparable to those observed in warm Galactic Halo clouds and significantly smaller than those in cool disc clouds, implying that some dust destruction occurs in H II regions. Boulanger et al. (2006) inferred the dust size distribution from a model of the wind swept shell SED. Their model suggests that dust evolution from the PDR to the HII gas occurs through large dust grains grinding in very small grains and the destruction of the smallest grains. Galliano et al. (2003) reached the same conclusion in their analysis of the SED of the dwarf star forming galaxy NGC 1569. Further work is required to see if the dust evolution from neutral PDRs to the ionized gas may explain observed differences in UV extinction between 30 Doradus and non-30 Doradus stars in the LMC (Misselt et al. 1999).

5. CONCLUSION

30 Doradus is often considered as a nearby template of star burst galaxies. The various perspectives opened by the analysis of 30 Doradus observations provide general insight to interpret observations of massive star formation in more distant galaxies. Our understanding of the radiative and dynamical impact of the R136 cluster on the interstellar medium structure and dust composition provides insight on massive stars feedback. One interesting perspective which needs to be further characterized and analyzed in relation to star formation is the impact of the R136 cluster on the structure of its surrounding molecular clouds.

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