The Interstellar Medium of Young Stellar Clusters from the Mid-Infrared Point of View

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Abstract. Effects of young stellar clusters on their gas and dust environment are probed using mid-infrared (MIR) wavelengths. The strong MIR [NeIII]/[NeII] ratios (~5 to 10) reveal the presence of current massive stars less than 5 Myr. Using MIR line ratios along with optical and NIR data from the literature, composite SEDs are constructed for NGC 1569, NGC 1140 and II Zw40. The stellar SEDs are then used as input to a dust model to study the impact of the hard, penetrating radiation field on the dust components, particularly in low metallicity environments, where the destructive effects of the massive stellar clusters on the environments occur on global scales. For example, the smallest dust particles are destroyed over larger regions in the dwarf galaxies than in normal metallicity starbursts.

1. Introduction

The subject of stellar cluster formation history and environment has made great headway lately, with the high resolution and sensitivity currently available at optical and near infrared (NIR) wavelengths. In principle, the mid-infrared (MIR) wavelength regime should provide numerous advantages for such studies, since this wavelength range is relatively extinction free ($A_{15\mu m} \sim 5\% A_J$) and contains diagnostic ionic lines to probe HII regions. In addition, hot dust emission provides us with another link to the ultraviolet starlight that has been absorbed and reemitted by the nearby grains. Our knowledge of the MIR wavelength window has been limited by the low spatial and spectral resolution provided by the IRAS satellite, and has remained rather sketchy when it comes to detailed studies of the ISM of individual galaxies. The Infrared Space Observatory (ISO; Kessler et al. 1996) has been a recent turning point in this effort, providing high spectral and spatial resolution and unprecedented sensitivity in the MIR through the far infrared (FIR). We have incorporated these MIR and FIR observations in a study of the energy redistribution in starburst galaxies, with the aim of understanding the impact of the star formation on the surrounding gas and dust.

The main limitation in MIR star cluster studies remains the spatial resolution, despite the great improvement over previous instrumentation provided by ISOCAM (~6′′ at 15µm; Cesarsky, C.J. et al. 1996). ISOCAM resolves about 600 pc at 20 Mpc, the distance of the closest massive merging system, the Antennae. However, even with this limitation, we are able to draw noteworthy
conclusions from the MIR, from unique MIR diagnostics. Here, I concentrate primarily on results of the nearer dwarf galaxies, since impacts of the massive clusters on the global dust and gas environment are very pronounced in these relatively small objects.

2. What Do MIR Wavelengths Trace?

Figure 1 shows ISOCAM 5-17 $\mu$m spectra for the three dwarf galaxies II Zw40, NGC 1140 and NGC 1569, with metallicities of $1/7$ to $1/3 Z_\odot$ (Madden et al. 2000), along with the spectrum of the notoriously metal poor SBS 0335-052 ($1/40 Z_\odot$; Thuan, Sauvage, & Madden 1999). All these spectra show obvious MIR signatures of massive stars.

As often seen in starburst galaxies, the MIR spectra are dominated by steeply rising continua longward of $\sim 10 \mu$m. Thermal emission from hot small grains with mean temperatures of the order of hundreds of Kelvin are responsible for the MIR continuum emission.

The unidentified infrared bands (UIBs) at 6.2, 7.7, 8.6, 11.3 and 12.6 $\mu$m, have been attributed to aromatic hydrocarbon particles undergoing stochastic temperature fluctuations (i.e., PAHs: Léger & Puget 1984; Allamandola, Tielens, & Barker 1989; coal grains: Papoular, Reynaud, & Nenner 1991). They are observed to peak in the photodissociation (PDR) zones around H II regions, but are destroyed deep within the HII regions themselves (Verstraete et al. 1996; Cesarsky, D. et al. 1996; Tran 1998). While the UIBs are not obvious in the spectra of II Zw40 and SBS 0335-052, and are only very weakly present NGC 1569, they can be distinguished in the spectrum of NGC 1140. Several ground state fine structure nebular lines are present also in 3 of the spectra, the most prominent being 15.6 $\mu$m [NeIII] (ionisation potential $\sim 41$ eV) and 10.5 $\mu$m [SIV] ($\sim 35$ eV). Weaker, lower energy lines may also present, such as the 8.9 $\mu$m [ArIII] line and the [NeII] 12.8 $\mu$m line, which can be blended with the 12.6 $\mu$m UIB.

While all of these spectra are very different from one another, all differ significantly from those of normal metallicity starburst galaxies. Normal starburst galaxies show prominent UIBs, in contrast to AGNs, which are devoid of UIBs (e.g., Roche et al. 1991; Dudley 1999, Laurent et al. 2000; Sturm et al. 2000). When compared to spectra characteristic of PDRs and HII regions (e.g., M17, Cesarsky, D. et al. 1996; Verstraete et al. 1996), II Zw40 is remarkably similar to that of an HII region. In contrast, NGC 1140, which has a very flat continuum yet a very strong [NeIII] line, does have a more obvious contribution from PDR regions in its spectra. Note that the MIR spectrum of N66, the most prominent HII region in the SMC, also shows a scarcity of UIBs in the vicinity of the most massive central cluster (Contursi et al. 2000), as does the low metallicity source NGC 5253 (Crowther et al. 1999).

In some starburst galaxies, amorphous silicate is seen in absorption centered at 9 and 18 $\mu$m (Roche et al. 1991; Dudley 1999; Laurent et al. 2000). We can fit the MIR region of the II Zw40 spectrum with a blackbody at 193 K and an absorption equivalent to $A_v \sim 4$. Dust temperatures derived assuming blackbodies should be interpreted with care, since the dust emitting in the MIR is expected to be undergoing stochastic processes rather than being in thermal equilibrium with the radiation field. The amount of absorption in II Zw40 ($A_v \sim$
Figure 1. MIR ISOCAM spectra of the dwarf galaxies II Zw40, NGC 1569, NGC 1140 and SBS 0335-052. The horizontal lines for SBS 0335-052 are broad band measurements; the dashed line is a black-body with $A_v \sim 20$ (from Thuan, Sauvage & Madden 1999). Note the absorption at $\sim 9$ and $18 \mu m$ in SBS 0335-052, attributed to amorphous silicates.

4) has yet to be confirmed. In SBS 0335-052, $A_v \sim 20$ has been deduced from the absorption in the ISOCAM MIR spectra (Fig. 1). The presence of a significant amount of dust at a metallicity as low as $Z_\odot/40$ is surprising, especially since star formation in SBS 0335-052 began as recently as 100 Myr ago (Papaderos et al. 1998; Thuan, Izotov, & Foltz 1999). Such high extinction implies that the current star formation rate, hidden by dust, might be underestimated by at least 50% (Thuan, Sauvage & Madden 1999).

3. Effects of the Massive Star Formation on the Gas

As a consequence of the smaller dust abundance of most dwarf galaxies, the ISM throughout these galaxies is affected by the hard radiation field of the massive stellar clusters. All star forming dwarf galaxies contain evidence for
Wolf-Rayet stars (Schaerer, Contini, & Pindao 1999) and super star clusters have been detected in NGC 1140 (Hunter, O’Connell, & Gallagher 1994), NGC 1569 (O’Connell, Gallagher, & Hunter 1994) and SBS 0335-052 (Thuan, Izotov, & Lipovetsky 1997). Their harsh radiation fields, which more readily permeate the ISM compared those in solar metallicity environments, are capable of destroying the UIB carriers, for example, over very extensive spatial areas. The effect of the pervasive radiation field can be witnessed in NGC 1569 (Fig. 2), where photodissociation occurs on global scales. Violent activity is revealed by the $\text{H}\alpha$ distribution (Waller 1991; Martin 1998) and the 15.8 $\mu$m $[\text{NeIII}]$ emission, with giant streamers suspected to originate from the energetic winds of the super star clusters A & B, (black stars in Fig. 2). The UIB, [SIV] and [NeIII] emission seems to avoid the super star clusters, which blow out much of the gas and dust on relatively short time scales. This effect is also seen in the CO (Taylor et al. 1999), HI (Israel & van Driel 1990) and $\text{H}\alpha$ (Waller 1991) distributions. Likewise we see the destruction of the UIBs in the beam-averaged spectrum of the entire galaxies II Zw40 and SBS 0335-052 (the available spatial resolution prevents us from seeing more detail within these galaxies in the MIR).

Figure 2. NGC 1569: $\text{H}\alpha$ (image) (Waller 1991) and 15.8 $\mu$m $[\text{NeIII}]$ emission contours. Note the extended $[\text{NeIII}]$ filaments, also seen in $\text{H}\alpha$. The 2 black stars mark the positions of the super star clusters A and B (O’Connell et al. 1994) which are devoid of $[\text{NeIII}]$ emission.
4. Modelling the Spectral Energy Distribution

We have compiled broad band data from the literature for II Zw40, NGC 1569 and NGC 1140 and have combined these with our MIR data to construct appropriate stellar spectral energy distributions (SEDs). In so doing, we fit the observed optical and NIR data with population synthesis models of PEGASE (Fioc & Rocca-Volmerange 1997), taking into account the constraints of the MIR line emission by modelling the corresponding photoionisation with CLOUDY (Ferland 1996). After briefly describing the results of this process, we discuss the results of the use of the reconstructed stellar SEDs as input to our dust model.

4.1. Combined stellar evolution and photoionisation model results

When assuming instantaneous star formation, a metallicity $Z_{\odot}/5$ and a Salpeter IMF (with upper and lower mass cut-offs of 0.1 and 120 solar masses), we find solutions to the observed broad band colours for a variety of ages and ionisation parameters. The ISOCAM MIR observations provide the diagnostic lines of neon, sulphur and argon, that have been recently addressed e.g. by Lutz et al. (1998), Crowther et al. (1999), Schaerer & Stasińska (1999) and Genzel et al. (1998).

For example, the $[\text{NeIII}]/[\text{NeII}]$ ratio is a measure of $T_{\text{eff}}$, the hardness of the radiation field, and therefore traces the massive stellar population. For the dwarf galaxies, we find $[\text{NeIII}]/[\text{NeII}]$ ratios in the range of 5 to 10 - much higher values than those of normal metallicity galaxies ($\leq 1$; Thornley et al. 2000). The extreme values of the $[\text{NeIII}]/[\text{NeII}]$ ratios are related to the low metallicities of the systems: the $T_{\text{eff}}$ of the stars increases as the metallicity decreases for a specific stellar age. High ratios of $[\text{NeIII}]/[\text{NeII}]$ and the prominent [SIV] in these spectra limit the age of the present star formation to $< 5$ Myr. Beyond this age, the massive stars have died and the $[\text{NeIII}]/[\text{NeII}]$ ratio drops dramatically. The high excitation 24.9 $\mu$m [OIV] line, covered by the ISO SWS data, is observed in some dwarf galaxies (Lutz et al. 1998) and has been attributed to the presence of Wolf-Rayet stars (Schaerer & Stasińska 1999).

For NGC 1569, NGC 1140 and II Zw40, we construct composite stellar SEDs that require 70 to 95% of the stellar mass to be provided by an 'older' population with ages between about 10 and 30 Myr, with the remaining 5% to 30% corresponding to a very young population ($< 5$ Myr). Observational evidence for the presence of Wolf-Rayet stars corroborates the existence of this very young stellar population (Vacca & Conti 1992). The broad band optical and NIR data alone reveal predominantly the older population in our apertures. Fig. 3 shows an example of the resultant composite SED for II Zw 40, including the extreme ultraviolet (EUV) radiation that the young, massive stellar population traces.

4.2. Effects of the Massive Star Formation on the Dust

We use the modelled stellar spectra of II Zw40, NGC 1569 and NGC 1140 as input to a dust model to study the effects of this radiation field on the dust properties. This is an important step since dust plays a major role in influencing the chemical and physical state of the ISM. We use the Désert, Boulanger, & Puget (1990) model to fit the various dust components emitting in the MIR and the FIR. This model calculates the IR emission from large silicate grains.
Figure 3. II Zw40 SED. The synthetic stellar spectra are fits to the extinction-corrected optical and NIR data from the literature for a 12" aperture using PEGASE. The 12, 25, 60 and 100 µm data are from IRAS and the 7 and 15 µm data points are integrated over 5.0 to 8.5 µm and 12.0 to 17 µm bands, respectively, using the ISOCAM spectrum (Fig. 1). A composite SED is shown, with a 5% contribution in mass from a young population (~ 3 Myr) and 95% from an “older” (10 Myr) population, which provides most of the observed optical and NIR fluxes.

(BGs), very small amorphous carbon grains (VSGs), and stochastically heated polycyclic aromatic hydrocarbons (PAHs), for various grain size distributions.

In these three galaxies the MIR spectrum is clearly dominated by emission from VSGs with very little PAH emission. The BG component dominates the overall dust emission with mass fractions ranging from 93% to 99%, while the PAH mass fraction is relatively insignificant — 5 orders of magnitude lower. The model gives a PAH/VSG mass ratio of $2 - 3 \times 10^{-4}$ for NGC 1569 and II Zw 40 and 10 times this value for NGC 1140. For comparison, the Désert et al. model applied to the Galactic cirrus gives a PAH/VSG mass ratio ~ 1. Thus, even compared to the VSG population, we find an insignificant mass fraction of PAHs, reflecting the fact that the PAHs are destroyed throughout the entire galaxies, as a result of the hard radiation fields originating from the few massive stellar clusters. This in an important result, since PAHs are thought to be the primary particles responsible for the photoelectric heating process (Bakes & Tielens 1994) and are incorporated in PDR models (Kaufman et al. 1999). Our preliminary results, while not statistically robust at this stage, suggest that even in the absence of PAHs, the photoelectric effect is efficient, as both II Zw40 and NGC 1569 are relatively prominent [CII] sources among the galaxies surveyed (Jones et al. 1997). On the contrary, in NGC 1140, where PAHs are more obvious
in the MIR spectra (Fig. 1), we do not detect [CII]. VSGs with derived sizes of \( \sim 40 \) to 300 \AA, which are very abundant relative to the PAHs in NGC 1569 and II Zw40 but less so in NGC 1140, may therefore be the more efficient sources of photoelectric gas heating in these environments, rather than PAHs.

This scenario is in contrast to normal metallicity galaxies, where the PAHs are prominently observed, and the effects of the numerous massive stellar activity are much more local rather than global.

5. Summary

MIR ISOCAM spectroscopy provides details of ionic lines, UIBs and the distribution of small hot grain emission in dwarf galaxies. The strong MIR [NeIII]/[NeII] ratios are signatures of the hard radiation fields and indicate the presence of clusters of young massive stars in dwarf galaxies. Because of the increase in \( T_{\text{eff}} \) in low metallicity environments, this ratio is enhanced in dwarf galaxies to at least 5 to 10 times that observed in normal metallicity galaxies. The penetrating radiation field also affects the dust components, destroying the UIBs in some dwarf galaxies on global scales, as is evident in the MIR spectra and in the dust modeling. This dramatic global effect of the massive stellar population in dwarf galaxies, due to the decrease in attenuation of the UV flux, is not apparent in normal metallicity galaxies, where these effects are experienced much more locally.

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References

Allamandola, L.J., Tielens, A.G.G.M., & Barker, J.R. 1989, ApJS, 71, 733
Bakes, E.L.O., & Tielens, A.G.G.M. 1994, ApJ, 427, 822
Cesarsky, C.J., Abergel, A., Agnese, P. et al. 1996 A&A, 315, 32.
Cesarsky, D., Lequeux, J., Abergel et al. 1996, A&A, 315, L309
Contursi, A., Lequeux, J., Cesarsky, D. et al. 2000, submitted to A&A
Crowther, P.A., Beck, S. C., Willis et al. 1999, MNRAS, 304, 645
Désert, F.-X., Boulanger, F., & Puget, J.-L. A&A, 237, 215
Dudley, C.C. 1999, MNRAS, 307, 553
Ferland, G.J. 1996, Int. Rep. Dept. of Physics, Univ. of Kentucky
Fioc, M. Rocca-Volmerange, B. 1997, A&A, 326, 950
Genzel, R. et al. 1998, ApJ, 498, 579
Hunter, D. A., R. W. O’Connell, R. W., Gallagher, J.S 1994, AJ, 108, 84
Israel, F. P., van Driel, W. 1990, ApJ, 236, 323
Jones, A.P., Madden, S.C., Colgan, S.W.J. et al. 1997, in Extragalactic Astronomy in the Infrared, ed. G. Mamon, T. Thuan, & J.Tran Than (Paris: Editions Frontières), 101
Kaufman, M.J., Wolfire, M.G., Hollenbach, D.J. & Luhman, M. L. 1999, ApJ527, 795
Kessler, M. F. et al. 1996, A&A, 315, L27
Laurent, O., Mirabel, I.F., Charmandaris, V. et al 2000, A&A, submitted.
Léger, A., Puget, J.-L. 1984, A&A, 137, L5
Lutz, D., Kunze, D., Spoon, H. W. W., Thornley, M. D. 1998, ApJ, 333, L75
Madden, S.C., Ragaigne, D., Jones, A. et al. 2000, in preparation
Martin, C. L. 1998, ApJ, 506, 222
O’Connell, R. W., Gallagher, J. S., & Hunter, D. A 1994, ApJ443, 65
Papaderos, P., Izotov, Y. I., Fricke et al. 1998, ApJ, 338, 43
Papoular, R., Reynaud, C., Nenner, I. 1991, A&A, 247, 215
Roche, P. F., Aitken, D. K., Smith, C. H., Ward, M.J. 1991, MNRAS, 248, 606
Schaerer, D., Contini, T., Pindao, M. 1999, A&A, 136, 35
Schaerer, D. & Stasińska, G. 1999, 345, A&A, L17
Sturm, E., Lutz,D., Tran, D. et al. 2000 A&A, in press
Taylor, C. L., Hüttemeister, S., Klein, U., Greve, A. 1999, A&A, 349, 424
Thornley, M. D., Förster Schreiber, N. M., Lutz et al. 2000, ApJ, submitted.
Thuan, T. X., Izotov, Y. I., Lipovetsky, V. A. 1997, ApJ, 477, 661
Thuan, T. X., Izotov, Y. I., Foltz, C. B. 1999 ApJ, 525, 105
Thuan, T. X., Sauvage, M., Madden, S. C. 1999 ApJ, 516, 783
Tran, D. 1998, Ph. D. Thesis, Université Paris XI
Vacca, W. D., Conti, P. S. 1992, ApJ, 401, 543
Verstraete, L., Puget, J.-L., Falgarone, E. et al. 1996, A&A, 315, L337
Waller, W. H. 1991, ApJ, 370, 144