INFRARED PROPERTIES OF STAR-FORMING REGIONS AND LINKS WITH STARBURST GALAXIES

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ABSTRACT

Four stellar complexes (star forming regions) in the LMC have been investigated using IRAS observations and starcounts in the optical region (U magnitude). The optical data allow us to detect such structures and give information on the age range of their stellar component. Under the assumptions of this age range, a Salpeter IMF and two different mechanisms of star formation rate (instantaneous and constant), we derived the expected flux in the optical and infrared wavelengths in order to compare them with the observed ones.

The expected flux at the U magnitude (in the optical window) for the adopted range of ages ($10^{6.5} - 10^{8.5}$ years) has been found comparable to the one derived from our starcounts within the errors. However, the infrared luminosity has been found to exceed systematically at least 10 times the U luminosity. We suggest that the excess far-infrared energy must be searched to the far UV radiation wavelengths.

Key words: star-forming regions; infrared properties; star-burst galaxies.

1. INTRODUCTION

Stellar complexes are the major large scale structures in a galaxy where very recent star formation occurs (Efremov & Chernin 1994). These regions have dimensions from 250-1200 pc, and they contain very young stellar component in the form of stars, stellar associations and clusters with ages not exceeding a few $\times 10^8$yr (Kontizas et al., 1996). The optical image of these regions is dominated by the most massive stellar component of O and B SpT main sequence stars and possibly the few M supergiants and Carbon stars. The infrared fluxes detected comes from dust, pre-main sequence stars and protostars.

From a search of such regions on the wide field photographic plates (direct and objective prism plates) taken with the 1.2m U.K. Schmidt Telescope in Australia, it is found that the stellar complexes can be revealed as concentrations of enhanced stellar number density compared to their surrounding regions (Kontizas et al. 1996, Maragoudaki et al. 1998).

Four of the LMC stellar complexes which have been detected from direct and objective prism plates (Kontizas et al. 1996, Maragoudaki et al. 1998) are discussed here. The stellar content was found from the distribution of spectral types down to $M_v \approx 0.0$ whereas the morphology and extension of these complexes was determined for star counts down to $M_v \approx +2.5$mag. The far infrared (FIR) properties of Shapley I has been investigated in the past by Meaburn & Laspias (1991). The estimated (from IRAS observations) number of O5 and earlier supergiants is in agreement with the results of Kontizas et al. (1994) obtained from the spectral classification.

In the present investigation we will compare the properties of the four selected complexes in the infrared from the IRAS images with those properties derived from the optical observations (star count and spectral classification). The regions studied by Kontizas et al. (1996) and Maragoudaki et al. (1998) will be used as characteristic star forming regions in a galaxy and their properties will be compared with those of starburst galaxies. Therefore, criteria of starburst galaxies in the FIR (without active nuclei) and stellar evolutionary models with an IMF are used to provide the connection of starburst regions to starburst galaxies.

2. OBSERVATIONAL MATERIAL

We combine data in the optical and IR wavelengths for four stellar complexes in the LMC.

2.1. Optical data

The observational material and the derived properties of the four selected complexes are described in detail by Kontizas et al. (1996) and Maragoudaki et al. (1998).

Proceedings of the Conference "The Universe as seen by ISO", Paris, France, 20–23 October 1998 (ESA SP-427, March 1999)

Direct plates taken from the U.K. Schmidt Telescope were used in order to perform star counts and reveal enhancements of number density of stars above 2-3 σ the average local background, down to $V \approx 21.0mag$. Objective prism plates from the same telescope were used in order to classify the stars in the complexes and derive the distribution of spectral types within the defined area down to $V \approx 18.5mag$. Comparison with nearby fields allow us to derive the actual number of stars per spectral type and the total number of stars down to the detection limit.

2.2. Infrared data

IRAS data at 12, 25, 60 and 100 μm have been used, in order to derive the IR fluxes for the selected regions. The derived infrared flux corresponds to the IRAS data of the optically defined complex.

3. METHODOLOGY

The procedure of our investigation implies the following steps:

- Derivation of the observed flux in the optical waveband.
- Derivation of the observed IR flux from the IRAS images.
- Derivation of the predicted total flux in the optical from the available data under the appropriate assumptions.

3.1. Total observed flux in the optical waveband

It is known that the dominant stellar component of the complexes are the O, B stars, therefore the optical flux of these regions is very well represented by the flux in the U magnitude.

Having found the boundaries of the selected complexes (Kontizas et al. 1996, Maragoudaki et al. 1998) we derive the total number of stars down to the detection limit after subtraction of the superimposed field stars. The adopted complex region of Shapley-I and the two nearby regions which were used to represent the local background for the subtraction of field stars (normalized to the same area) is illustrated as an example, in Figure 1. This procedure was performed for various magnitude ranges and therefore the total number of stars provides the total U flux of the complex.

3.2. Total observed flux in the infrared

In order to calculate the IR flux we used IRAS observations at 12, 25, 60 and 100 μm for the regions corresponding to the selected complexes. A value of the background flux has been derived from the mean IR flux of the whole LMC IRAS image per unit area.

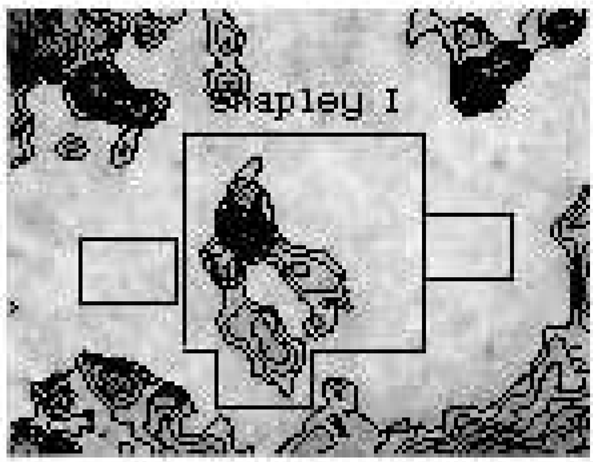

Figure 1. The complex region of Shapley I, as it was revealed from the isopleth maps on star counts in the U waveband. The nearby regions which were adopted as representative of the local background, are also shown.

The total IR fluxes (background subtracted) for the selected complexes are given in Table 1.

Table 1. The observed infrared fluxes (Jy) of the selected complexes and the ratio f_{60}/f_{100}

Complex	12 μm	25 μm	60 μm	100 μm	f_{60}/f_{100}
Shapley I	52	160	1451	2463	0.59
Shapley IV	7.8	2.4	139	560	0.24
Shapley IX	30	43	546	1430	0.38
Shapley X	207	1412	7527	7722	0.97

3.3. Predicted flux

The optical data provide basic information on the age of the stellar complexes and a total number of stars at certain magnitudes. Assuming a set of stellar ages, an IMF and two star formation rates we can find the total flux at the required optical and IR wavelengths.

In an extended search for the detection of stellar complexes in the LMC it is found that the main stellar component involved cannot be older than a few times $10^8 yr$ (Maragoudaki et al. 1998). Thus, we have used models of stellar evolution at ages $10^{6.5} yr$ (for the very young and the most massive stellar component) and $10^{8.5} yr$ (for the older stellar population). Moreover, Massey (1998) has found that the slope of the IMF for LMC, SMC and our Galaxy's massive stellar component in clusters and associations is ~ 1.3 despite their large metallicity differences. Thus, we accepted a Salpeter IMF slope for the four stellar complexes. This assumption is in agreement

Table 2. Total fluxes in U and IR waveband of the selected complexes. The fluxes are measured in $10^{40} erg.s^{-1}$

Complex	Observed U	Predicted U for $t = 10^{6}.5$yrs	Predicted U for $t = 10^{8}$yrs	Observed IR.
Shapley I	0.13	0.22	0.034	2.6
Shapley IV	0.98	0.14	0.021	0.38
Shapley IX	0.42	0.033	0.005	1.9
Shapley X	0.25	0.084	0.013	11

with the observed LF of the studied complexes for the range of magnitudes corresponding to the brightest stars ($14.0 < U_{mag} < 17.0$) within the observational errors.

We have also taken into consideration two different models of star formation rate, one corresponding to constant $\dot{M}$, and one for instantaneous star formation.

Following the above assumptions, we derived the predicted flux with normalising point at the number of stars for $U_{mag} \sim 16.5$.

4. RESULTS AND DISCUSSION

According to Heckman (1990, 1996) one criterion for star-burst galaxies is based on the ratio of $\frac{f_{60}}{f_{100}} > 0.5$. This criterion is fulfilled for Shapley I and Shapley X and this could be also a criterion for a starburst region in a galaxy. Those ratios are shown in Table 1.

The total fluxes in the optical and FIR wavelength for the four selected regions are given in Table 2. The total FIR luminosity is estimated as $L_{IR} = 3.65 \times 10^5 (2.58 f_{60} + f_{100}) D^2 L_\odot$ (Devereux & Eales 1989).

We can also see that the FIR luminosity is systematically larger than the U luminosity of this region (Table 2). Thus, we suggest that the excess FIR luminosity should be searched to the far UV radiation.

Grosso et al. (these proceedings) combined the IR and X-ray deep surveys to study the young population in extremely young cluster embedded in the nearby star-forming clouds and confirmed that essentially all IR sources are X-ray emitters.

From the isochrones and the number of stars with $U < 18.5$ we can estimate also the total mass of the young stellar component. Specifically we obtain that $100\,M_\odot$ correspond to 4 such luminous stars if the age is $10^{6.5}$yrs and to 2 stars if the age is 10^8years. On the other hand we can estimate the star formation rate from the total IR radiation as $\dot{M} = 26 L_{IR,11} M_\odot.yr^{-1}$ (Hunter et al. 1986) where $L_{IR,11}$ is the total IR luminosity in $10^{11} L_\odot$.

According to Hunter et al. (1986) the above relation is valid for the situation when all the UV radiation is absorbed by the dust. If only a fraction is absorbed, then the star formation rate should be multiplied by q=(total UV radiation)/(absorbed UV radiation). If the star formation rate is underestimated, then the age is overestimated. In the present situation it is safe to assume that q is not much larger than unity and also there is nothing to indicate that the star formation rate was constant.

For Shapley I we have $L_{IR} = 6.85 \times 10^6 L_\odot$ and for Shapley X we have $L_{IR} = 3 \times 10^7 L_\odot$. Consequently we obtain star formation rates $\dot{M} = 1.8 \times 10^{-3} M_\odot.yr^{-1}$, $\dot{M} = 7.8 \times 10^{-3} M_\odot.yr^{-1}$ for Shapley I and Shapley X respectively. In table 3 the total masses of the complexes are presented by the assumption of age equal to 10^8yrs. The mass becomes twice as small if the age is $10^{6.5}$yrs. Finally, the age listed in Table 3 is calculated under the assumption that the star formation rate was constant and the mass is the corresponding to age 10^8yrs (Table 3). We do not give any estimation of the age of Shapley IV, Shapley IX because they do not satisfy the conditions of a starburst region and also the contrast in luminosity between them and the field is very small. So the IR radiation possibly is not related to a recent starburst.

The estimated ages of Shapley I, Shapley X show a very good agreement with the results of (Kontizas et al. 1996).

Table 3. The total stellar mass and the estimated ages.

Complex	Observed Total Mass $M_\odot$	Predicted Age yr
I	2×10^5	2×10^8
IV	1×10^5	-
IX	5×10^4	-
X	6×10^4	8×10^6

We will try to estimate the temperature of the dust. We expect that we have cold and hot dust. The temperature of the cold dust is estimated from the luminosities at 60, $100\,\mu$m. We assume an emission coefficient proportional to ν. From $f_{60} = 990$ Jy, $f_{100} = 1815$ Jy (Meaburn & Laspias 1991) we obtain $T_d = 37$ K. From $f_{60} = 1451$ Jy, $f_{100} = 2463$ Jy we obtain $T_d = 38$ K. From $f_{60} = 7527$ Jy, $f_{100} = 7722$ Jy we obtain $T_d = 48$ K.

In all the above situations the radiation of the dust at 12, $25\,\mu$m is much smaller than that we observe so we ignore its radiation at the smaller IRAS wavelengths. The luminosity of the stars at 12, $25\,\mu$m is also very small so the only possible candidates for that radiation are the hot dust and the HI clouds. If we assume that the contribution of the HI clouds is small, then the temperature of the dust should be 150 K for Shapley I, 130 K for Shapley X (130 and 110 in case of emission coefficient proportional to ν^2). If we ignore the role of the dust and assume black-body clouds, from the fluxes at 12, 25 μm we obtain T=190, 150 K, respectively. The estimation of the temperature of the hot dust is in agreement with the predictions of the hot dust model (Bernlohr 1993) in Shapley X and Shapley I for the ν^2 case whereas the estimation of the temperature of the HI clouds is higher than the temperature of the HI clouds of our galaxy. Nevertheless in Shapley I the error due to the background is large. The enormous resulted temperature of the HI clouds means either that the role of the radiation of the HI clouds is negligible, or that they have been heated by the radiation of ionization fronts due to the UV radiation of OB-stars or shock waves due to supernova explosions. Another important factor is the HII regions. According to Wainscoat et al. (1992) $f_{12}/f_{25} \simeq 0.13$. This ratio corresponds to temperature equal to 126 K when the emission coefficient is proportional to ν so the resulted temperature of the dust, slightly depends on any assumption about the importance of the IR radiation of HII regions. From the above discussion we understand that the predicted temperature of the hot dust is in agreement with the hot dust grains model.

ACKNOWLEDGMENTS

The authors would like to thank the U.K. Schmidt Telescope Unit for loan of the optical observational material. They would also like to express their thanks to the General Secretariat of Research & Technology, to PPARC (grant number GR/K98728) and to the EC TMR Network programme (FMRX-CT96-0068) for their financial support.

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