ABSTRACT

We review the characteristics of the dust continuum emission from normal galaxies, as revealed by the ISOPHOT Virgo Cluster Deep Survey (Tuffs et al. 2002; Popescu et al. 2002, Popescu & Tuffs 2002b).

1. INTRODUCTION

The ISOPHOT Virgo Cluster Deep Survey (Tuffs et al. 2002; Popescu et al. 2002) represents the deepest survey (both in luminosity and surface brightness terms) of normal galaxies yet measured in the Far-Infrared (FIR). The survey consists of 63 gas-rich Virgo Cluster galaxies selected from the Virgo Cluster Catalog (VCC; Binggeli, Sandage & Tammann 1985; see also Binggeli, Popescu & Tammann 1993) and measured using the ISOPHOT instrument (Lemke et al. 1996) on board ISO (Kessler et al. 1996).

The fundamental incentive for choosing the VCC as the basis of a statistical sample for ISOPHOT was that a luminosity- and volume-limited sample of cluster periphery and cluster core galaxies representative of the field and cluster environments, respectively, could be observed down to the least luminous dwarf galaxies reachable with ISOPHOT. This should allow an investigation of the strength and time-dependence of all manifestations of star formation activity and its relation to intrinsic galaxy properties such as Hubble type or sheer overall size. From an observational point of view the Virgo cluster has the advantage that it is situated at high galactic latitude and is close to the ideal distance for the detection of dwarf galaxies with ISOPHOT. The VCC has also a full representation of morphological types of normal gas rich galaxies, including quiescent systems and even, to some extent, low surface brightness objects, ranging from bright \(B_T \sim 10\) giant spirals down to blue compact dwarfs (BCDs) and irregular galaxies at the completeness level of \(B_T \sim 18\).

Thus, the VCC is ideal for providing the basis for statistical investigations of the FIR properties of gas rich galaxies in the local universe spanning a broad range in star-formation activity and morphological types, including dwarf systems.

2. THE OBSERVATIONS

The observations were done using the C100 and C200 detectors, in ISOPHOT’s “P32” observing mode (Tuffs & Gabriel 2002a,b), which uses the focal plane chopper in conjunction with a spacecraft raster to rapidly sample large areas of sky. The observing wavelengths were 60, 100 and 170\(\mu\)m. The “P32” mode allowed the entire optical extent of each target down to the 25.5 mag arcsec\(^{-2}\) B-band isophote and adjacent background to be scanned, while still maintaining a spatial oversampling. This allowed both spatially integrated FIR photometry as well as information on the morphology of the galaxies in the FIR to be extracted. The data were reduced using the new P32 software algorithm of Tuffs & Gabriel (2002a,b). An example of an observation of the Sb spiral VCC 66 is given in Fig. 1.

From the 63 galaxies observed (61 galaxies at all three FIR wavelengths and 2 galaxies only at 100 and 170\(\mu\)m) we detected 54 galaxies at least at one wavelength and 40 galaxies at all three wavelengths. The averaged 3\(\sigma\) upper limits for integrated flux densities of point sources at 60, 100 and 170\(\mu\)m are 43, 33 and 58 mJy, respectively. The
Figure 2. Examples of FIR SEDs from the ISOPHOT Virgo Cluster Deep Sample (Popescu et al. 2002). The colour corrected flux densities at 60, 100 and 170 $\mu$m are plotted together with their associated error bars. One galaxy, VCC 1110, has additional measurements at 70 and 120 $\mu$m. The two modified black-body functions which best fitted the data points are plotted with dashed lines. The temperature of the warm component is constrained to be 47 K. The fitted temperature of the cold component is marked near each fit. The sum of the two fitting functions is plotted as the solid line. Some galaxies (see text) don’t show evidence for two dust components and their SEDs are fitted with single component modified black-body functions, plotted as solid lines.

The sample of VCC galaxies selected for ISOPHOT also formed a substantial part of samples observed with ISO using the ISOCAM MIR camera in pass bands centred at 6.9 and 15 $\mu$m (Boselli et al. 1997b, 1998) and the LWS at the 158 $\mu$m [CII] fine structure gas cooling line (Leech et al. 1999). In particular, the latter observations provide complementary information about the energetics of the interstellar gas, the sources of [CII] emission within the interstellar medium (Pierini et al. 1999, 2001), and the role played by different stellar populations in the gas heating.

3. The FIR spectral energy distributions

We fitted the observed spectral energy distributions (SEDs) with a superposition of two modified black-body functions, physically identified with a localised warm dust emission component associated with HII regions (whose temperature was constrained to be 47 K), and a diffuse emission component of cold dust. The two temperature components are in fact predicted by the SED modelling of Popescu et al. (2000a), which self-consistently analyses the UV/optical/NIR and the FIR/submm SEDs, and can account for both the integrated flux densities and the surface brightness distribution over the whole spectral range. The model[1], which includes solving the radiative-transfer problem for a realistic distribution of absorbers and emitters, considering realistic models for dust, taking into account the grain-size distribution and stochastic heating of small grains and the contribution of HII regions, has not only the power to derive the star-formation rates and star-formation histories, but can also predict the relative contribution of the young and old stellar populations to the dust emission as a function of wavelength (see Fig. 3).

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[1] Full details of the model are given by Popescu et al. (2000a), Misiriotis et al. (2001) and Popescu & Tuffs (2002a).
Despite the complexity of the model, which calculates a continuous distribution in dust temperatures, it can be seen that a natural outcome of this modelling technique is the prediction of a diffuse cold component of dust emission powered by a combination of non-ionising UV and optical-NIR photons, and a warm component of dust emission corresponding to the ensemble of discrete HII regions. This corresponds to what we have seen in the ISOPHOT maps of Virgo galaxies.

Thus, the emerging result from the FIR SED fits was that most of the Virgo galaxies from our sample require both warm and cold dust emission components to be fitted. The cold dust temperatures is broadly distributed, with a median of 18 K (Popescu et al. 2002), some 8–10 K lower than would have been predicted by IRAS. The corresponding dust masses were correspondingly found to be increased by factors of typically 6–13 with respect with previous IRAS determinations. As a consequence, the derived gas-to-dust ratios are much closer to the canonical value of ∼160 for the Milky Way but with a broad distribution of values (Popescu et al. 2002).

A good linear correlation is found between the “warm FIR” luminosities and the Hα equivalent widths (EW), supporting the assumptions of our constrained spectral energy distribution (SED) fit procedure. We also found a good non-linear correlation between the “cold FIR” luminosities and the Hα EWs, consistent with the prediction of Popescu et al. (2000a) that the FIR-submm emission should mainly be due to diffuse non-ionising UV photons. Both the “warm” and the “cold” FIR luminosity components are non-linearly correlated with the (predominantly non-thermal) radio luminosities (Popescu et al. 2002). The validity of the FIR-radio correlation was thus tested using for the first time measurements of the bulk of the dust emission in quiescent normal galaxies, making this a highlight result of the ISOPHOT Virgo investigation.

Another highlight result is the calculation of the percentage of stellar light re-radiated by dust. Previous estimates based on the IRAS Bright Galaxy Sample (BGS; Soifer & Neugebauer 1991) have established a canonical value of 30% for the fraction of starlight to be re-radiated in the FIR in the local universe. However, this value refers to relatively bright FIR sources in which the bulk of the dust emission is radiated in the IRAS 60 and 100 µm bands, and is not representative of quiescent systems like the Virgo galaxies. In addition it takes no account of measurements longwards of 120 µm, not available at that time. The percentage of stellar light re-radiated by dust was investigated by Xu & Buat (1995), using an indirect estimate for the total FIR luminosity. With the advantage of the new ISOPHOT data we calculate this percentage by using for the first time measurements of the bulk of the dust emission in quiescent normal galaxies.

By combining the luminosity of dust emission with the observed UV/optical/NIR luminosities derived from the data of Schröder & Visvanathan (1996), Boselli et al. (1997), Rifatto, Longo & Capaccioli (1995) and Deharveng et al. (1994) we show that the mean percentage is ∼30% for the later spirals in the ISOPHOT Virgo Cluster Deep Sample (Popescu & Tuffs 2002b). This value is the same as the canonical value of 30% obtained for the IRAS BGS by Soifer & Neugebauer (1991). This is probably due to the fact that there are two factors influencing this percentage, and working in opposite directions. The addition of the ISO cold dust luminosity increases the FIR contribution to the total bolometrics. But our sample consists of more quiescent galaxies than those from BGS and we expect them to have smaller FIR contributions. By the same token, it is probable that the contribution of dust emission to the total luminosity of the BGS galaxies will be greater than the 30% derived from IRAS.

**4. Trends with Hubble Type**

Of particular interest are the results concerning the trends with Hubble type. A tendency was found for the temperatures of the cold dust component to become colder, and for the cold dust surface densities (normalised to optical area) to increase with increasing lateness in the Hubble type (Figs. 4a,b). A particularly surprising result was the low dust temperatures (ranging down to less than 10 K) and large dust masses associated with the Virgo Im and Blue Compact Dwarf (BCD) galaxies. Another important trend is the increase of the normalised (to K′ band magnitude) FIR luminosity as we progress from the early to the later Hubble types (Fig. 4c). This result was later confirmed by Bendo et al. (2002) for the RSA (Revised Shapley-Ames Catalog) sample. A related result was also obtained by Pierini et al. (1999) for the LWS data on Virgo galaxies, where a strong correlation of normalised [CII] emission with Hα equivalent widths was interpreted as a trend of increasing star-formation rate along the Hubble sequence.
Figure 4. Trends with Hubble type. The distribution of a) cold dust temperatures $T_{\text{cold}}$; b) cold dust mass surface densities $M_{\text{cold}}^D/D^2$; c) normalised FIR luminosity (to the $K'$ band magnitude) for different Hubble types. The hatched histograms represent the distributions for the galaxies with SEDs fitted by only one dust component. The filled histograms represent the distributions for the galaxies with detections only at 100 and 170 $\mu$m. For the latter cases the dust temperatures are only upper limits and the dust masses are only lower limits.

Finally, we found an increase of the ratio of the dust emission to the total stellar emitted output along the Hubble sequence. This correlation is quite strong, ranging from typical values of $\sim 15\%$ for early spirals to up to $\sim 50\%$ for some late spirals (Popescu & Tuffs 2002b). This, together with the trend for a decrease in the temperature of the cold dust, would suggest a trend of increasing opacities with increasing star-formation activity. The extreme BCDs can have even higher percentages of their bolometric output re-radiated in the thermal infrared. This correlation can be also interpreted as a sequence from normal to dwarf gas rich galaxies, with the dwarfs having an increased contribution of the FIR output to the total bolometric output. These findings could be important for our perception of the distant Universe, where, according to the hierarchical galaxy formation scenarios, gas rich dwarf galaxies should prevail. We would then expect these galaxies to make a higher contribution to the total FIR output in the early Universe than previously expected. This, together with the cosmic-ray driven winds, in which grains can survive and be inserted in the surrounding intergalactic medium (Popescu et al. 2000b), could potentially change our view of the high-redshifted Universe.

5. Cold dust in the Virgo BCDs

Perhaps the most intriguing result of this investigation are the masses and temperatures of the cold dust derived for the Im and BCD galaxies in our sample. These systems are clearly differentiated from the spirals, having the highest
dust mass surface densities (normalised to optical size), and the lowest dust temperatures. This is a particularly unexpected result, since the IRAS observations of BCDs could be accounted for in terms of dust heated locally in HII regions, with temperatures of 30 K or more.

The unexpected result that large amounts of cold dust exist in some Virgo BCDs was interpreted by us as being indicative of dust surrounding the optical galaxy, originating in an external dust reservoir fact, in two cases direct evidence was found of resolved emission at 170 micron on scales of up to 10 kpc. To qualitatively account for the FIR and optical extinction characteristics of BCDs, Popescu et al. (2002) proposed two scenarios invoking collisionally or photon-heated emission from grains originating in the surrounding intergalactic medium. In the one scenario, grains are swept up from a surrounding protogalactic cloud and heated collisionally in an optically thin wind bubble blown from the BCD. In the other, the grains are taken to be photon-heated in an optically thick disk surrounding the optical galaxy. The disk is indicative of a massive gas/dust accreting phase which makes dwarf galaxies sporadically bright optical-UV sources when viewed out of the equatorial plane of the disk. In both scenarios the dust does not have a galactic origin, but needs to exist in the immediate vicinity of the galaxies, where it can either be heated by winds or can accrete into the dwarfs.

REFERENCES

Bendo, G.J., Joseph, R.D., Wells, M. et al. 2002b, AJ in press
Binggeli, B., Popescu, C.C. & Tammann, G.A. 1993, A&AS, 98, 275
Binggeli, B., Sandage, A. & Tammann, G.A. 1985, AJ, 90, 1681
Boselli, A., Tuffs, R. J., Gavazzi, G., Hippelein, H., & Pierini, D., 1997, A&AS, 121, 507
Boselli, A., Lequeux, J., Contursi, A., et al. 1997, A&A, 324, L13
Boselli, A., Lequeux, J., Sauvage, M., et al. 1998, A&A, 335, 53
Deharveng, J.-M., Sasseen, T. P., Buat, V. et al. 1994, A&A, 289, 715
Kessler, M. F., Steinz, J. A., Anderegg, M. E., et al. 1996, A&A, 315, 27
Leech, K. J., Völk, H. J., Heinrichsen, I., Hippelein, H., Metcalfe, L., Pierini, D., Popescu, C. C., Tuffs, R. J., & Xu, C. 1999, MNRAS, 310, 317
Lemke, D., Klaas, U., Abolins, J. et al. 1996, A&A, 315, L64
Misiriotis A., Popescu, C. C., Tuffs, R. J., & Kylafis, N. D. 2000, A&A, 372, 775
Pierini, D., Leech, K. J., Tuffs, R. J., & Völk, H. J. 1999, MNRAS 303, L29
Pierini, D., Lequeux, J., Boselli, A., Leech, K. J., & Völk, H. J. 2001, A&A, 373, 827
Popescu, C. C., Misiriotis A., Kylafis, N. D., Tuffs, R. J., & Fischera, J., 2000a, A&A, 362, 138
Popescu, C. C., Tuffs, R. J., Fischera, J. & Völk, H. J. 2000b, A&A, 354, 480
Popescu, C.C. & Tuffs, R. J. 2002a, Reviews in Modern Astronomy, vol 15.