A BIAS IN OPTICAL OBSERVATIONS OF HIGH REDSHIFT LUMINOUS INFRARED GALAXIES

V. CHARMANDARIS
Astronomy Department, Cornell University, Ithaca, NY 14853, USA
vassilis@astro.cornell.edu

E. LE FLOC’H, I.F. MIRABEL
CEA/DSM/DAPNIA, Service d’Astrophysique, F-91191 Gif-sur-Yvette, France
elefloch@as.arizona.edu, fmirabel@cea.fr

ABSTRACT

We present evidence for the dramatically different morphology of galaxies between the rest frame UV and mid-IR emission at z > 0. Nearly all LIRGs are interacting systems and it is currently accepted that they dominate the IR emission at z > 1. Luminous IR galaxies located at z = 1–2 could easily be detected as unresolved sources in deep optical/near-IR ground based surveys, as well as in upcoming 24μm surveys with the Space Infrared Telescope Facility. We demonstrate that the spatial resolution of these surveys will result in blending of the emission from unresolved interacting components. An increased scatter will thus be introduced in the observed optical to mid-IR colors of these galaxies, leading to a systematic underestimation of their dust content.

Subject headings: infrared: galaxies – ultraviolet: galaxies – galaxies: individual (Arp 299, VV 114) – galaxies: high-redshift – galaxies: starburst – galaxies: irregular

1. INTRODUCTION

Over the past decade several studies on the physical characteristics of high redshift galaxies have revealed a number of new exciting results. In particular it has been established that the star formation rate (SFR) of both individual galaxies, as well as the SFR per co-moving volume, increases by more than an order of magnitude as we move from systems of the local Universe to those found at a redshift of z ≥ 2 (e.g., Steidel et al. 1996; Madau et al. 1998). The details on exactly how the SFR evolves at even higher redshifts are still under debate as they are strongly affected by small number statistics on the properties of the population of the sources detected in sub-mm surveys, but more importantly by the accurate modeling of the effects of dust extinction. A number of deep surveys — most notably the Hubble Deep Field — have also shown that a large number of faint galaxies at intermediate and high redshift display irregular and/or disturbed morphology as well as an excess of blue light emission (see Williams et al. 1996; Abraham et al. 1996; Le Fèvre et al. 2000). A way to explain this faint blue excess in the galaxy luminosity function is by introducing a rapidly evolving population of star forming galaxies at those redshifts (Glazebrook et al. 1995; Metcalfe et al. 2001). What are the properties though, of this population? Several researchers suggest that these distant galaxies are a new class of systems which are physically small in size (Pascarelle et al. 1996), while others speculate that they are high redshift analogues of local interacting galaxies. The latter scenario can be understood since these distant galaxies may look peculiar because of the k-correction and band shifting of their short wavelength (UV) emission to the optical HST filters (Hibbard & Vacca 1997, and references therein).

Two additional independent findings seem to suggest that galaxy interactions may indeed have significant implications to the blue excess in the galaxy luminosity function. The first one is the ample evidence that the galaxy interaction/merge rate increases as a power law function of redshift ∼ (1+z)^m (Carlberg 1990; Lavery et al. 1996). Even though a direct observational measure of the interacting/merging galaxy pairs, and hence m, has been difficult due to a number of potential biases in surveys, current estimates indicate that m can be as high as 3–4.5 (see Lavery et al. 1996; Le Fèvre et al. 2000, for a review). The second is that phenomena associated with galaxy interactions such as the presence of starburst, infrared luminous, and ultraluminous (LIRGs/ULIRGs) galaxies detected with IRAS also increase with redshift (e.g., Lonsdale et al. 1990; Sanders & Mirabel 1996; Xu et al. 2001). Tidally triggered massive star formation in galaxies, which may eventually transform gas rich galaxies into their ultraluminous phase, will be responsible for increasing their rest frame UV flux and hence for the blue color excess of the galaxies detected in deep surveys. It is also the reason why large quantities (∼ 10^11 M⊙) of molecular gas may be compressed over an area of few hundred pc around their nuclei (Downes & Solomon 1998; Bryant & Scoville 1999) eventually obscuring them behind large quantities of dust. As a result, wavelength dependent extinction by dust grains distorts the morphology of interacting galaxies, limiting our ability to accurately probe their properties. A prime example of this phenomenon was displayed in the study of NGC 4038/39 ("The Antennae") by Mirabel et al. (1998). This system of interacting galaxies, located at...
distance of 20 Mpc is only moderately infrared luminous\(^4\) \((L_{\text{IR}}=4.9\times 10^{10} L_\odot)\) and still contains considerable quantities of molecular gas dispersed over a large area, which may become available for a more intense star formation event in the future (Wilson et al. 2000). Despite that, half of the mid-IR flux of the system originates from the optically obscured overlap region between the two nuclei (see Mirabel et al. 1998).

It is thus reasonable to pose the following questions. How would the morphology of systems more IR luminous than NGC 4038/39 be affected by the presence of dust and what consequences this may have in measurements of the spatially unresolved IR luminous galaxies which are readily discovered at high \((z \gtrsim 1.5)\) redshift? More specifically, how might this affect the conclusions of color correlations between a number of optical and near-IR surveys that are performed from the ground (e.g., Jannuzi & Dey 1999), and those scheduled to be performed with the Space Infrared Telescope Facility (SIRTF) (e.g., Rieke et al. 2000; Lonsdale 2003)\(^5\)?

We will base our analysis on high resolution UV and mid-IR observations of Arp 299 and VV 114 that became recently available. Both galaxies have IR luminosities almost an order of magnitude higher than NGC 4038/39 \((L_{\text{IR}} \sim 5 \times 10^{11} L_\odot)\) for Arp 299 and \(\sim 4 \times 10^{11} L_\odot\) for VV 114 but the projected spatial separation between their two interacting components is still sufficiently large (8 and 6 kpc respectively) for us to be able to resolve them given their proximity (41 and 80 Mpc respectively).

2. OBSERVATIONS

All observations used in this paper were retrieved from previously published work and we refer the reader to those publications for details on the data reduction. The mid-IR data were obtained with ISOCAM on board the Infrared Space Observatory (ISO) and were presented by Le Floc’h et al. (2002) for VV 114 and by Charmandaris et al. (2002) for Arp 299. The UV data of both galaxies were retrieved from the HST archive. An analysis of the STIS images of VV 114 and FOC images Arp 299 is included in Goldader et al. (2002) and Meurer et al. (1995) respectively.

3. DISCUSSION

3.1. Dust and interactions at high-z

A detailed study of the apparent morphology of peculiar galaxies as a function of redshift was already performed by Hibbard & Vacca (1997) by examining UV and optical images of a sample of 4 interacting galaxies. These authors found that at \(z \gtrsim 1.5\) it is no longer possible to discern features such as long tidal tails and bridges that would identify these systems as clearly "interacting", even in exposures as deep as the Hubble Deep Field. These authors also alluded that the redshifted rest UV light, which will be sampled in the optical if those galaxies are at \(z \gtrsim 1.5\), can not be used to accurately image the evolved stellar population.

The limitations discussed by Hibbard & Vacca (1997) become even stronger if one considers dust extinction\(^5\).

Even though numerous \(z \sim 2-3\) galaxies have been detected as UV drop outs, the actual magnitude of extinction effects in the detection of distant galaxies using their rest frame UV emission is still under debate (see Meurer et al. 1999; Adelberger & Steidel 2000, for conflicting views). However, a number of recent results clearly suggest the presence of considerable quantities of dust at high redshifts. Based on a UV selected sample of 16 galaxies at \(2 \leq z \leq 2.6\), Erb et al. (2003) found that the SFR, measured using the redshifted into the K-band H\(\alpha\) line, is not only elevated \((16 M_\odot yr^{-1})\) but it is also a factor of \(\sim 2.4\) higher than that estimated using their UV continuum (SFR\(_{UV}\)). This discrepancy in estimating the SFR is even higher for the systems with low UV luminosity and can be easily understood due to the presence of dust. Unfortunately no H\(\beta\) line was detected from these galaxies to measure their Balmer decrement, and consequently we can not be certain whether the factor of 2.4 is just a lower limit. Furthermore, UV selected samples may be biased towards systems with a low dust content. A similar underestimate in SFR\(_{UV}\) compared to the one calculated using the H\(\beta\) line was found for a small sample of galaxies at \(z = 3\) by Pettini et al. (2001). Even at lower redshifts though \((z \sim 1)\), where larger samples and better statistics are available, the presence of dust is evident and new rather interesting trends emerge. In an analysis of a large sample of galaxies located at \(0.4 \leq z \leq 0.8\) Cardiel et al. (2003) estimated their SFR using the IR luminosity as well as their H\(\alpha\) emission. They found a clear trend indicating that as one moves from lower to higher luminosity systems \((L_{\text{IR}} = 10^{11} - 10^{12} L_\odot)\) the SFR\(_{H\alpha}\) is up to an order of magnitude less than the SFR\(_{IR}\) (see their Fig. 15) in agreement with the original work by Armus et al. (1990) based on IRAS data.

The result of Cardiel et al. (2003) further supports our concern that the effects of dust in the \(z \sim 2\) IR luminous systems mentioned earlier may not have been properly taken into account. It also stresses the need to better quantify the correlation between the rest frame mid-IR emission and the L\(_{IR}\) of IR luminous galaxies (Chary & Elbaz 2001), since a strong active galactic nucleus (AGN) can also contribute to the mid-IR (see Laurent et al. 2000; Tran et al. 2001).

3.2. Arp 299 and VV 114 analogues in high-z surveys

To better illustrate another aspect of the influence of dust in the morphology of an IR luminous galaxy, we decided to compare the UV and 7\(\mu\)m images of Arp 299 and VV 114, the two nearest interacting pairs of galaxies with L\(_{IR} > 10^{11}\), which at the same time are sufficiently extended in the sky (see Fig. 1). Both systems show a clearly resolved eastern and western component. As they have been studied extensively in all wavelengths we had access to published high resolution UV images with HST, mid-IR images with Keck (Soifer et al. 2001), as well as our own deep mid-IR images obtained with ISOCAM (see Le Floc’h et al. 2002; Charmandaris et al. 2002, and references therein).

The selection of the rest frame \(\sim 0.2\mu\text{m}\) (UV) and \(\sim 7\mu\text{m}\) (mid-IR) bands was determined by the fact that at \(z \sim 2\)

\(^4\) We use the standard definition of L\(_{IR}\)\((8–1000\mu\text{m}) = 5.62 \times 10^5 D(\text{Mpc})^2 \left(13.48 f_{12} + 5.16 f_{25} + 2.58 f_{60} + f_{100}\right) L_\odot\) (see Sanders & Mirabel 1996), H\(\alpha = 75 \text{ km s}^{-1} \text{Mpc}^{-1}\), and \(q_0 = 0.5\) to facilitate comparison with earlier work.

\(^5\) We note that if we were to trace dust using the usual extinction law A\(\nu\), then A\(_{UV}\)\(\sim 7 A_{H\alpha}\)\(\sim 270 A_{7\mu m}\) (Mathis 1990).
Table 1. The distribution of both galaxy components to the total emission further enhances its mid-IR emission. The relative contribution of its mid-IR flux originates from the UV! VV 114E actually displays strong evidence that more extreme. Although VV 114E is 2.5 times brighter and mid-IR wavelengths. The situation in VV 114 is even more complicated if an obscured AGN is present since this will increase the 3–6 μm mid-IR emission but it will have minimal effects in the UV flux. To address these limitations, follow-up observations with deep near-IR sub-arcsec imaging using the Hubble Space Telescope or high-quality ground facilities will be necessary in order to reveal whether those systems are indeed substantially disturbed and help us understand their physical properties.

3.3. Frequency of “VV 114-type systems at high-z

An interesting question to address would be how important/numerous galaxies with properties similar to VV 114 are at high-z. The fact that the extreme characteristics of VV 114 were realized based on high resolution UV and mid-IR maps, which are available for only a handful of the nearby LIRGs/ULIRGs, makes such a prediction challenging. However, if we use the 1Jy sample of Kim et al. (2002) as a guide, we find that ~10% of the systems have interacting pairs with similar spatial separation to VV 114 and an R-K color of one galaxy in the system being more than 2 mags different than the other one. For VV 114 this color difference is 3.5 mag. Even though LIRGs and ULIRGs are rare in the local Universe contributing to less than 6% of the local infrared emission (see Sanders & Mirabel 1996), they are much more frequent at high-z. The ISO-CAM deep surveys clearly demonstrate that at z~1 nearly 65% of the peak and integrated cosmic infrared background originates from galaxies. Of those galaxies, ~75% are LIRGs and ULIRGs (see review by Elbaz & Cesarsky 2003). Furthermore, as we mentioned earlier, it is accepted that LIRGs/ULIRGs are the result of galaxy merging and

considered as a single system the UV emission from the less obscured component dilutes the signature of warm dust emission. Hence, if one is to use the X_{MIR}^{UV} reddening or even estimate the slope b of the UV spectrum to establish a b to L_{FIR} correlation as tracer of extinction and total dust content (i.e., Meurer et al. 1999) in IR luminous systems, a systematic underestimate of the dust content will be introduced.

This fact has serious implications when one tries to examine the colors of distant high redshift sources using deep surveys with low or moderate spatial resolution. All IR luminous galaxies are very likely interacting systems. A significant fraction of them, similarly to the two cases presented above, will remain as unresolved point sources. Even though the actual value of the rest frame mid-IR to UV ratio depends on the details of the filters used to observe the high-z sources (R, I, and/or MIPS24), and they are beyond the scope of this letter, one result is clear from this exercise. A simple diagnostic which correlates integrated rest frame UV with mid-IR or radio measurement is bound to introduce a systematic scatter not just due to the unknown quantities of dust at high-z, but principally due to the blending of the emission from the unresolved interacting components. Depending on the stage of the interaction and the amount of spatially extended star formation activity, there will be cases (such as VV 114) where this scatter may be extreme. The situation will be even more complicated if an obscured AGN is present since this will increase the 3–6 μm mid-IR emission but it will have minimal effects in the UV flux. To address these limitations, follow-up observations with deep near-IR sub-arcsec imaging using the Hubble Space Telescope or high-quality ground facilities will be necessary in order to reveal whether those systems are indeed substantially disturbed and help us understand their physical properties.

6 For more information on the NOAO Deep Wide-Field Survey visit http://www.noao.edu/noao/noaodeep

7 For more information on MIPS and its sensitivity visit http://mips.as.arizona.edu.

8 Unfortunately, lack of high spatial resolution UV and mid-IR maps for a statistically significant sample of local IR luminous galaxies makes a quantitative prediction of this scatter impossible.
it has been found that even though interacting systems comprise only 3–9% of all local galaxies (Arp & Madore 1975; Struck 1999), the merger rate increases rapidly with redshift \((1+z)^{1.6}\) out to \(z\sim3\) (Conselice et al. 2003) and most high-z galaxies appear somewhat perturbed. Based on the above results a simple scaling would suggest that systems such as VV 114 may contribute \(\sim5–10\)% to the galaxy counts in the infrared at \(z\geq1\). So even though extremely rare locally, systems such as VV 114 may have profound effects in our understanding of the early Universe.

4. CONCLUSIONS

Using archival images of VV 114 and Arp 299, two nearby violently interacting infrared luminous galaxies, we show the strikingly different morphology between their 0.2 \(\mu\)m UV and 7 \(\mu\)m mid-IR emission. Even though the redshifted rest frame emission from both wavelengths will be easily detected at \(z\sim2\) by ground based R-/I-band surveys and by the 24 \(\mu\)m surveys of SIRTF respectively, the fact that we will not be able to spatially resolve the different components of each source will introduce a scatter in their measured colors. This scatter will not only depend on the relative contribution of each interacting component to the total IR luminosity, but it will also cause a systematic underestimate of the integrated rest frame mid-IR to UV colors leading to lower values of the total dust content of those systems.

We thank the anonymous referee whose comments helped us improve this paper. VC would like to thank J.R. Houck (Cornell), D. Elbaz (CEA/Saclay), L. Armus (Caltech), J. Hibbard (NRAO), and J.D. Smith (Arizona) for useful discussions, as well as to acknowledge the support of JPL contract 960863.

REFERENCES

Abraham, R. G., Tanvir, N. R., Santiago, B. X., Ellis, R. S., Glazebrook, K., & van den Bergh, S. 1996, MNRAS, 279, L47
Adelberger, K. L., & Steidel, C. C. 2000, ApJ, 544, 218
Armus, L., Heckman, T. M., & Miley, G. K. 1990, ApJ, 364, 471
Arp, H. A., & Madore, B. F. 1975, The Observatory, 95, 212
Bryant, P. M., & Scoville, N. Z. 1999, AJ, 117, 2632
Cardiel, N., Elbaz, D., Schiavon, R. P., Willmer, C. N. A., Koo, D. C., Phillips, A. C., & Gallego, J. 2003, ApJ, 584, 76
Carlberg, R. G. 1990, ApJ, 359, L1
Charmandaris, V., Stacey, G. J., & Gull, G. 2002, ApJ, 571, 282
Chary, R., & Elbaz, D. 2001, ApJ, 556, 562
Conselice, C. J., Bershady, M. A., Dickinson, M., & Papovich, C. 2003, AJ, 126, 1183
Downes, D., & Solomon, P. M. 1998, ApJ, 507, 615
Elbaz, D. & Cesarsky, C. J. 2001, ApJS, 137, 87
Erb, D. W., Shapley, A. E., Steidel, C. C., Pettini, M., Adelberger, K. L., Hunt, M. P., Moorwood, A. F. M., & Cuby, J.-G. 2003, ApJ, 591, 101
Glazebrook, K., Ellis, R., Santiago, B., & Griffiths, R. 1995, MNRAS, 275, L19
Goldader, J. D., Meurer, G., Heckman, T. M., Seibert, M., Sanders, D. B., Calzetti, D., & Steidel, C. C. 2002, ApJ, 568, 651
Hibbard, J. E., & Vacca, W. D. 1997, AJ, 114, 1741
Jannuzi, B. T., & Dey, A. 1999, ASP Conf. Ser. 191: Photometric Redshifts and the Detection of High Redshift Galaxies, 111
Kim, D.-C., Phillips, A. C., & Gallego, J. 2003, ApJ, 584, 76
Le Floc'h, E., Charmandaris, V., Laurent, O., Mirabel, I. F., Gallaix, P., Sauvage, M., Vignoux, L., & Cesarsky, C. 2002, A&A, 391, 417
Le Floc’h, E., Charmandaris, V., Laurent, O., Mirabel, I. F., Gallaix, P., Sauvage, M., Vignoux, L., & Cesarsky, C. 2002, A&A, 391, 417
Madau, P., Pozzetti, L., Dickinson, M. 1998, MNRAS, 498, 106
Mathis, J. S. 1990, ARAA, 28, 37
Metcalfe, N., Shanks, T., Campos, A., McCracken, H. J., & Fong, R. 2001, MNRAS, 323, 795
Meurer, G. R., Heckman, T. M., Leitherer, C., Kinney, A., Robert, C., & Garnett, D. R. 1995, AJ, 110, 2665
Meurer, G. R., Heckman, T. M., & Calzetti, D. 1999, ApJ, 521, 64
Mirabel, I. F., et al., 1998, A&A, 333, L1
Pascarelle, S. M., Windhorst, R. A., Keel, W. C., & Odewahn, S. C. 1996, Nature, 383, 45
Pettini, M., Shapley, A. E., Steidel, C. C., Cuby, J., Dickinson, M., Moorwood, A. F. M., Adelberger, K. L., & Giavalisco, M. 2001, ApJ, 554, 981
Rieke, M. J., et al. 2000, AAS Meeting, 197, #77.13
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Soifer, B. T., et al., 2001, AJ, 122, 1213
Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJ, 462, L17
Struck, C. 1999, Phys. Rep., 321, 1
Tran, Q. D., et al. 2001, ApJ, 552, 527
Williams, R. E., et al. 1996, AJ, 112, 1335
Wilson, C. D., Scoville, N. Z., Madden, S. C., & Charmandaris, V. 2000, ApJ, 542, 120
Xu, C., Lonsdale, C. J., Slupe, D. L., O’Linger, J., & Masci, F. 2001, ApJ, 562, 179
|            | Arp 299 | IC 694 | NGC 3690 | VV 114 | VV 114E | VV 114W |
|------------|---------|--------|----------|--------|---------|---------|
| UV (≈0.22 μm) (mag)\(^a\) | 12.73  | 14.55  | 12.95    | 14.49  | 18.38   | 14.53   |
| mid-IR (≈7 μm) (mJy)\(^b\)  | 1032   | 325    | 707      | 202    | 136     | 66      |
| \(X_{UV}^{MIR} = 7 \text{μm} / \text{UV}\)\(^c\) | 196    | 330    | 164      | 34     | 819     | 11      |

\(^a\)UV magnitudes based on Table 6 of Meurer et al. (1995) and Table 3 of Goldader et al. (2002).

\(^b\)The 7μm (LW2) ISO-CAM flux density over the same regions using data from Charmandaris et al. (2002) and Le Floc’h et al. (2002).

\(^c\)The non dimensional \(X_{UV}^{MIR}\) ratio is calculated after converting the UV mag to \(f_v\) in mJy.
Fig. 1.— a) An HST/STIS image of VV 114 at 0.23 \( \mu \)m, adapted from Goldader et al. (2002) with an overlay of the 7 \( \mu \)m emission from Le Floc’h et al. (2002). The images are uniform and the UV flux limit is 26.6 mag arcsec\(^{-2}\). The contour levels are set with logarithmic spacing between 0.8 and 8.4 mJy arcsec\(^{-2}\) (\(1\sigma \sim 0.15\) mJy arcsec\(^{-2}\)). b) An archival HST/FOC (0.22 \( \mu \)m) UV image of Arp 299 with the 7 \( \mu \)m emission contours from Charmandaris et al. (2002). The images are uniform and the UV flux limit is 21 mag arcsec\(^{-2}\). The contour limits are set to 1.2 and 30.7 mJy arcsec\(^{-2}\) (\(1\sigma \sim 0.27\) mJy arcsec\(^{-2}\)). Note the offset in the 7 \( \mu \)m centroid of IC 694 when compared to the underlying UV emission. c) The same UV image of Arp 299 with an overlay of the 38 \( \mu \)m emission from Charmandaris et al. (2002). The levels are 1.5 Jy beam\(^{-1}\) beginning at 3 Jy beam\(^{-1}\) (6\(\sigma\)). We can easily see that in both systems the rest frame UV light from the mid-IR dominant source is either completely suppressed (VV 114) or marginally detected (Arp 299), leading to the high scatter in the \(X_{MIR/UV}\) values of Table 1. For reference we include in a) a horizontal bar which indicates the physical scale of 8 kpc that 1 arcsec (the typical angular resolution of ground optical deep surveys) would cover if VV 114 were at \(z=2\). Note that the angular resolution of SIRTF at 8 and 24 \( \mu \)m is \(\sim 2.3\) and \(\sim 6.9\) arcsec respectively.