THE LUMINOSITY AND METALLICITY RELATION
OF DISTANT LUMINOUS INFRARED GALAXIES

Yanchun Liang\textsuperscript{1,2}, François Hammer\textsuperscript{2}, Hector Flores\textsuperscript{2}, David Elbaz\textsuperscript{3},
Delphine Marcillac\textsuperscript{3}, Lici Deng\textsuperscript{1} and Catherine J. Cesarsky\textsuperscript{4}
\textsuperscript{1}National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, P.R. China;
\textsuperscript{2}GEPI, Observatoire de Paris-Meudon, 92195 Meudon, France;
\textsuperscript{3}CEA, Saclay-Service d’Astrophysique, Orme des Merisiers, F91191, Gif-sur-Yvette, France;
\textsuperscript{4}ESO, Karl-Schwarzschild Strasse 2, D85748 Garching bei München, Germany
ycliang@bao.ac.cn

Abstract
A sample of 55 distant ($z > 0.4$) luminous infrared galaxies (LIRGs) selected
from ISOCAM deep survey fields (CFRS, UDSR, UDSF) have been studied
on the basis of their high-quality optical spectra from VLT/FORS2. We em-
phasize that the only way to derive O/H metal abundances with sufficient accu-
racy is by deriving the extinction and underlying Balmer absorption properly,
on the basis of good-S/N spectra of moderate resolution. Here, the extinction
coefficient is estimated via two independent methods, e.g., the Balmer-line ratio
$[A_V(\text{Balmer})]$ and the energy balance between the infrared and H$\beta$
luminosities $[A_V(\text{IR})]$, are internally consistent, with a median value of 2.36. Oxygen abun-
dances $[12+\log(O/H)]$ in the interstellar medium of the sample galaxies have
been estimated from the extinction corrected emission-line ratios, and show a
range from 8.36 to 8.93, with a median value of 8.67, which is 0.5 lower than
that of the local bright disks (i.e., $L^*$) at the given magnitude. A significant
fraction of distant large disks are indeed LIRGs. Such massive disks could have
formed $\sim 50\%$ of their metals and stellar masses since $z \sim 1$.

1. Introduction

The cosmic infrared background resolved by ISOCAM shows that the co-
moving density of infrared light due to the luminous infrared galaxies ($L_{IR} \geq 10^{11} L_\odot$; LIRGs) was more than 40 times greater at $z \sim 1$ than today (Elbaz et al. 2002). The main driver for this evolution is the emergence of luminous infrared starburst galaxies seen by ISO at $z > 0.4$ (Flores et al. 1999). Source counts and star-formation rates (SFRs) have been studied for the ISO-detected objects in the $z > 0.4$ Universe (Elbaz et al. 1999, Aussel et al. 1999, Flores et al. 1999, Franceschini et al. 2003). However, very little was known about the
chemical properties of distant LIRGs. In this paper, we present the chemical abundances of a large sample of distant \((z > 0.4)\) LIRGs selected from ISO-CAM deep survey fields (CFRS, UDSR, UDSF). We estimate their oxygen abundances in the interstellar medium (ISM) on the basis of their high-quality optical spectra from VLT/FORS2. In particular, this is the first time that the luminosity-metallicity (L-Z) relations of such a large sample of distant LIRGs are obtained.

In the local Universe, metallicity correlates well with the absolute luminosity (stellar mass) of galaxies over a wide magnitude range (e.g., \(7 - 9\) mag; Zaritsky et al. 1994, Richer & McCall 1995, Telles & Terlevich 1997, Contini et al. 2002, Melbourne & Salzer 2002, Lamareille et al. 2004, Tremonti et al. 2004). In the intermediate-redshift Universe, L-Z relations have also been obtained for some sample galaxies. Kobulnicky & Zaritsky (1999) found that the L-Z relation of 14 emission-line galaxies with \(0.1 < z < 0.5\) is consistent with that of the local spiral and irregular galaxies. The 16 CFRS galaxies at \(z \sim 0.2\) studied by Liang et al. (2004a) fall well into the region occupied by the local spiral galaxies. Kobulnicky et al. (2003) obtained the L-Z relation of 64 intermediate-z galaxies from the Deep Groth Strip Survey (DGSS). In the \(0.6 - 0.82\) redshift bin, their galaxies are brighter by \(\sim 2.4\) mag, compared to the local \((z < 0.1)\) field galaxies (Kennicutt 1992a,b, hereafter K92a,b; Jansen et al. 2000a,b, hereafter J20a,b). This result was confirmed by Maier et al. (2004). Kobulnicky & Kewley (2004) obtained the L-Z relation for 204 emission-line galaxies in the GOODS-N field, and showed a decrease in the average oxygen abundance of \(\sim 0.14\) dex from \(z = 0\) to \(z = 1\) for the galaxies with \(M_B\) from \(-18.5\) to \(-21.5\). These studies contrast with the result of Lilly et al. (2003), who found that the L-Z relation of most of their 66 CFRS galaxies with \(0.5 < z < 1\) is similar to that of the local galaxies from J20b. However, Lilly et al. (2003) assumed a constant \(A_V = 1\) in order to account for dust extinction. In this study, we investigate the L-Z relation for LIRGs at \(z > 0.4\) detected by ISO, after taking into account their underlying stellar absorption and dust extinction properties in detail.

Throughout this paper, a cosmological model with \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\), \(\Omega_M = 0.3\) and \(\Omega_{\Lambda} = 0.7\) has been adopted. \(M_B\) is given in the AB magnitude system.

2. Sample selection, observations and data reduction

The sample galaxies were selected from three ISO deep survey fields: the CFRS 3h field, the Ultra Deep Survey Rosat (UDSR) and the Ultra Deep Survey FIRBACK (UDSF) fields. In the CFRS 3h field, 70 sources were detected, with their 15 \(\mu\)m fluxes in the range of \(170 - 2100\ \mu\)Jy (Flores et al. 2004, 2005, in prep.). The UDSR field refers to the Marano field, which is a deep
The Luminosity and Metallicity Relation of distant luminous infrared galaxies

ROSAT field. FIRBACK is a deep survey conducted with the ISOPHOT instrument aboard ISO, at an effective wavelength of 175 µm. For the UDSR and UDSF fields, very deep ISOCAM follow-up observations have been obtained (Elbaz et al. 2005, in prep.) reaching flux limits three times lower than for the CFRS field.

In total, 105 objects were selected for our VLT/FORS2 spectral observations with R600 and I600, at a resolution of 5 Å and covering 5000 – 9200 Å. The slit width was 1.2 arcsec. Spectra were extracted and wavelength calibrated using the IRAF package. Flux calibration was done using 15-minute exposures of 3 photometric standard stars per field.

The redshift distribution of the sample galaxies shows a median value of 0.587, which is consistent with the results in some other ISOCAM survey fields (Flores et al. 1999, Aussel et al. 1999, Franceschini et al. 2003). Fifty five of the redshift-identified objects are distant LIRGs with \( z > 0.4 \).

The IR luminosities (and deduced SFRs) were calculated using the procedure given in Elbaz et al. (2002). The inferred IR luminosity (8 – 1000 µm) of the ISOCAM 15µm-detected objects with \( z > 0.4 \) shows a similar distribution as the local IRAS sample from Veilleux et al. (1995) and Kim et al. (1995), with a median value of \( \log \left( \frac{L_{\text{IR}}}{L_\odot} \right) = 11.32 \).

3. A robust estimate of the extinction coefficient

The extinction inside a galaxy can be derived using its Balmer decrement. For the \( z > 0.4 \) galaxies, \( H_\alpha \) is shifted to the near infrared, so that \( H_\gamma / H_\beta \) can be used to estimate the dust extinction. The stellar absorption under the Balmer lines was estimated from synthesized stellar spectra obtained using the stellar spectral library of Jacoby et al. (1984). We adopt the interstellar extinction law of Fitzpatrick (1999) with \( R = 3.1 \), and Case B recombination, with a density of 100 cm\(^{-3}\) and a temperature of 10,000 K to estimate the dust extinction. Subsequently, the extinction-corrected Balmer emission lines (either \( H_\beta \) or \( H_\alpha \)) were used to estimate the SFRs by adopting the calibrations from Kennicutt (1998) based on a Salpeter (1955) initial mass function (IMF; 0.1 and 100 M_\odot mass cut-offs). The derived SFR\(_{\text{Balmer}}\) could be compared with the SFR\(_{\text{IR}}\) obtained from the infrared flux. The two SFRs are consistent, and their median values are 28 and 31 M_\odot yr\(^{-1}\), respectively. This kind of consistency was also confirmed by Hopkins et al. (2003) for the SDSS galaxies, and by Kewley et al. (2002) for the Nearby Field Galaxies Survey sample of J20b.

Because of the large uncertainties related to the measurements of the \( H_\gamma \) line, we need to verify the quality of our derived extinction values. This can be done assuming that the infrared data provide a robust SFR estimate for IR-luminous galaxies (Elbaz et al. 2002, Flores et al. 2004). We estimate a new dust extinction coefficient, \( A_{V}(\text{IR}) \), by comparing SFR\(_{\text{IR}}\) and SFR\(_{2.87H_\beta}\), the
energy balance between the IR and H$\beta$ luminosities. Figure 1 shows that the derived $A_V$(IR) is consistent with $A_V$(Balmer) for most galaxies, most of them falling in the $\pm 0.64$ rms discrepancy. The derived median value of $A_V$(IR) is 2.36 for the $z > 0.4$ galaxies.

Figure 1. The relation between the extinction values derived from the Balmer decrement [$A_V$(Balmer)], and from the energy balance between the IR radiation and the optical H$\beta$ emission-line luminosities [$A_V$(IR)]. They are consistent with each other. The two dashed lines refer to the results with $\pm 0.64$ rms.

4. Abundances in the interstellar medium and the luminosity-metallicity relation

The chemical properties of the gas and stars in a galaxy are like a fossil record chronicling its history of star formation and its present evolutionary status. The high-quality optical spectra from VLT/FORS2 make it possible to obtain the chemical abundances of the ISM for these distant LIRGs. This will be the first data set of chemical abundances of a large sample of distant LIRGs.

The oxygen abundances of the distant LIRGs were estimated via the “strong-line” method ($R_{23}$ and $O_{32}$), using the calibration of Kolbinicky et al. (1999) for the metal-rich branch. The derived 12+$\log$(O/H) values of the galaxies range from 8.36 to 8.93, with a median value of 8.67.

Figure 2a compares the L-Z relation for the LIRGs to that of local disks (K92b, J20b), which are restricted to moderately star-forming [EW(H$\beta$) < 20 Å] galaxies, following Kobulnicky et al. (2003). Here we did not include other local samples selected based on their UV or H$\alpha$ emission; they mostly include low-luminosity (low-mass?) systems in the local Universe (Contini et al. 2002, Lamareille et al. 2004, Melbourne & Salzer 2002). We could not compare directly with the large sample of SDSS galaxies given by Tremonti et al. (2004) because of the large scatter of the data.
The distant LIRGs exhibit $\sim 0.3$ dex ($\sim 50\%$) lower oxygen abundances than local star-forming galaxies at the given magnitude (the median value). PÉGASE2 models (Fioc & Rocca-Volmerange 1999) predict a total mass ranging from $10^{11}$ M$_\odot$ to $\leq 10^{12}$ M$_\odot$ for the LIRGs, which can be twice the stellar masses of distant LIRGs ($1.4 \times 10^{10} - 2.9 \times 10^{11}$ M$_\odot$) derived by Zheng et al. (2004) on the basis of $K$-band luminosities. About 36% of LIRGs are large disks; a similar fraction (about 32%) is estimated from the sample of large disks of Lilly et al. (1998). These massive LIRGs have high SFRs. The timescale to double their stellar masses $T_{\text{SF}}$ can be short, i.e., $0.1 - 1$ Gyr. Such massive disks could have formed $\sim 50\%$ of their metals and stellar masses since $z \sim 1$. Hammer et al. (2004, 2005) have investigated whether the LIRG properties could be related to recent and significant star formation in massive galaxies, including spirals.

These distant LIRGs were also compared with two samples of galaxies in a similar redshift range, taken from Kobulnicky et al. (2003) [EW(H$\beta$) < 20 Å] and Lilly et al. (2003). Kobulnicky et al. (2003) estimated the O/H values using the $R_{23}$ and $O_{32}$ parameters obtained from the corresponding equivalent widths of the emission lines, which are believed to be less affected by dust extinction (Kobulnicky & Phillips 2003). The metallicities of their galaxies are similar to ours, but the galaxies are fainter at a given metallicity. This discrepancy in $M_B$ reflects that our sample galaxies are brighter and possibly more massive than the rest-frame blue-selected sample of DGSS galaxies (see Liang et al. 2004b for details).

The comparison with Lilly’s sample helps us to understand the strong effects of dust extinction on the derived oxygen abundances of galaxies. In Fig. 2b, Lilly’s sample has been restricted the galaxies in the CFRS 3h and 14h fields, the two fields surveyed by ISOCAM. The 10 ISO galaxies (the solid triangles) among the 42 sample galaxies show a median value of $12 + \log(O/H) = 8.98$, which is $\sim 0.3$ dex higher than the median value of our distant LIRGs. Indeed, Lilly et al. (2003) assumed a constant extinction of $A_V = 1$ for all their galaxies, which can underestimate the average extinction for LIRGs (which has a median value of 2.36), and consequently leads to underestimated $[O\text{II}]\lambda 3727/H\beta$ ratios, and hence to overestimated oxygen abundances. To estimate the chemical abundances of such distant LIRGs, underlying stellar absorption of Balmer lines and dust extinction should be considered carefully.

**Acknowledgments**

Yanchun Liang wishes to thank the Natural Science Foundation of China (NSFC) for travel support to attend this conference, also thank the NSFC support under No.10403006. We thank Dr. Richard de Grijs for his help to improve the English description.
Figure 2. The $M_B$-metallicity relation of our distant LIRGs (with a typical uncertainty of 0.08 dex on metallicity), compared with other samples: (a) with the local galaxies from K92b and J20b; PéGase2 infall models are superimposed, assuming a total mass of $10^{11}$ M$_\odot$ and infall times of 5 Gyr and 1 Gyr (solid and dashed lines with pentagons, respectively); (b) with the galaxies of Lilly et al. (2003). The linear least-squares fits to the samples are also given.

References

Aussel H., Cesarsky C.J., Elbaz D., Starck J.L., 1999, A&A, 342, 313
Contini T., Treyer M.A., Sullivan M., Ellis R.S., 2002, MNRAS 330, 75
Elbaz D., Cesarsky C.J., Chanial P., Aussel H., Franceschini A., Fadda D., Chary R.R., 2002, A&A, 384, 848
Elbaz D., et al., 2005, in prep.
Fioc M., Rocca-Volmerange B., 1999, astro-ph/9912179 (PéGase2)
Fitzpatrick E.L., 1999, PASP, 111, 63
Flores H., et al., 1999, ApJ, 517, 148
Flores H., Hammer F., Elbaz D., Cesarsky C.J., Liang Y.C., Fadda D., Gruel N., 2004, A&A, 415, 885
Flores H., et al., 2005, in prep.
Franceschini A., et al., 2003, A&A, 403, 501
Hammer F., Flores H, Zheng X.Z, Liang Y.C., 2004, these proceedings
Hammer F., Flores H., Elbaz D., Zheng X.Z., Liang Y.C., Cesarsky C.J., 2005, A&A, 430, 115
Hopkins A.M., et al., 2003, ApJ, 599, 971
Jacoby G. H., Hunter D. A., Christian C. A., 1984, ApJS, 56, 257
Jansen R.A., Franx M., Fabricant D., Caldwell N., 2000, ApJS, 126, 271 (J20a)
Jansen R.A., Fabricant D., Franx M., Caldwell N., 2000, ApJS, 126, 331 (J20b)
Kennicutt R.C. Jr., 1992a, ApJS, 79, 255 (K92a)
Kennicutt R.C. Jr., 1992b, ApJ, 388, 310 (K92b)
Kennicutt R.C. Jr., 1998, ARA&A, 36, 189
Kewley L.J., Geller M.J., Jansen R.A., Dopita M.A., 2002, AJ, 124, 3135
Kim D.-C., Sanders D.B., Veilleux S., Mazzarella J.M., Soifer B.T., 1995, ApJS, 98, 129
Kobulnicky H.A., Phillips A., 2003, ApJ 599, 1031
Kobulnicky H.A., Kennicutt R.C. Jr., Pizagno J.L., 1999, ApJ, 514, 544
Kobulnicky H.A., Kewley L.J., 2004, ApJ, 617, 240
Kobulnicky H.A., Zaritsky D., 1999, ApJ, 511, 118
Kobulnicky H.A., et al., 2003, ApJ, 599, 1006
Lamareille F., Mouhcine M., Contini T., Lewis I., Maddox S., 2004, MNRAS 350, 396
The Luminosity and Metallicity Relation of distant luminous infrared galaxies

Liang Y.C., Hammer F., Flores H., Gruel N., Assémat F., 2004a, A&A, 417, 905
Liang Y.C., Hammer F., Flores H., Elbaz D., Marcillac D., Cesarsky C.J., 2004b, A&A, 423, 867
Lilly S.J., Carollo C.M., Stockton A.N., 2003 ApJ, 597, 730
Lilly S.J., et al., 1998, ApJ, 500, 75
Maier C., Meisenheimer K., Hippelein H., 2004, A&A, 418, 475
Melbourne J., Salzer J.J., 2002, AJ, 123, 2302
Richer M.G., McCall M.L., 1995, ApJ, 445, 642
Salpeter E.E., 1955, ApJ, 121, 161
Telles E., Terlevich R., 1997, MNRAS, 286, 183
Tremonti C.A., et al., 2004, ApJ, 613, 898
Veilleux S., Kim D.-C., Sanders D.B., Mazzarella J.M., Soifer B.T., 1995, ApJS, 98, 171
Zaritsky D., Kennicutt R.C., Huchra J.P., 1994, ApJ, 420, 87
Zheng X.Z., Hammer F., Flores H., Assémat F., Pelat D., 2004, A&A, 421, 847