THE STAR FORMATION RATE FUNCTION OF THE LOCAL UNIVERSE

D. Christopher Martin,1 Mark Seibert,1 Véronique Buat,2 Jorge Iglesias-Páramo,2 Tom A. Barlow,1 Luciana Bianchi,1 Yong-Ik Byun,4 José Donas,7 Karl Forster,1 Peter G. Friedman,1 Timothy M. Heckman,5 Patrick N. Jelinsky,6 Young-Wook Lee,3 Barry F. Madore,7,8 Roger F. Malina,2 Bruno Milliard,2 Patrick F. Morrissey,1 Susan G. Neff,2 R. Michael Rich,10 David Schiminovich,1 Oswald H. W. Siegmund,6 Todd Small,1 Alex S. Szalay,5 Barry Y. Welsh,6 and Ted K. Wyder1
Received 2004 June 7; accepted 2004 August 31; published 2005 January 17

ABSTRACT

We have derived the bivariate luminosity function for the far-ultraviolet (1550 Å) and far-infrared (60 μm). We use matched GALEX and IRAS data, and redshifts from NED and the PSCz survey. We have derived a total star formation luminosity function φ(Ltot), with Ltot = L_{FUV} + L_{FIR}. Using these, we determined the cosmic “star formation rate” (SFR) function and density for the local universe. The total SFR function φ(L_{tot}) is fitted very well by a lognormal distribution over 5 decades of luminosity. We find that the bivariate luminosity function φ(L_{FUV}, L_{FIR}) shows a bimodal behavior, with L_{FIR} tracking L_{FUV} for L_{tot} < 10^{10} L_\odot and L_{FUV} saturating at ~10^{10} L_\odot, while L_{tot} ~ L_{FIR} for higher luminosities. We also calculate the SFR density and compare it with other measurements.

Subject headings: galaxies: evolution — galaxies: fundamental parameters — galaxies: luminosity function, mass function — infrared: galaxies — ultraviolet: galaxies

1. INTRODUCTION

The evolution of the density of the cosmic star formation rate (SFR) represents a fundamental constraint on the growth of stellar mass in galaxies over time (Madau et al. 1996; Fall et al. 1996). The distribution of star formation rates, or the “SFR function,” in galaxies is potentially also a fundamental constraint on cosmological models and on the physics of star formation in galaxies.

While a number of SFR metrics have been used in the past, perhaps the most direct measurement is the bolometric luminosity of massive stars, usually obtained from the sum of far-ultraviolet (FUV; 1350–1750 Å) and far-infrared (FIR; 60 μm) luminosities. With the launch of the Galaxy Evolution Explorer (GALEX) a large, homogeneous, magnitude-limited sample of UV measurements can be combined with the IRAS FIR sample to generate a true bolometric luminosity function in the local universe. As discussed in this volume by Buat et al. (2005), FUV- and FIR-selected samples have quite distinct FUV-to-FIR luminosity ratios. However, if the samples are large, homogeneous, flux limited, and deep enough in both bands, volume dependence can be removed and the fundamental bivariate distribution derived for either sample. To provide the most information, the samples can also be combined (Avni & Bahcall 1980).

Our goal in this Letter is to generate a bolometric luminosity function and luminosity density for the bands that sample recent star formation. We do this by using FUV-selected, FIR-selected, and combined samples to estimate the bivariate luminosity function (BVLF) in L_{FUV} and L_{FIR}, φ(L_{FUV}, L_{FIR}), using the V_{max} method. We then bin this BVLF into a single total luminosity function (TLF) φ(L_{tot}), where L_{tot} = L_{FUV} + L_{FIR}. We provide some simple parametric fits for the TLF and estimate the cosmic SFR density. We discuss whether FUV- and FIR-selected samples provide consistent measurements of these functions. We conclude with a brief discussion of the implications. Our cosmology is Ω_m = 0.3, Ω_Λ = 0.7, H_0 = 70 km s^{-1} Mpc^{-1}.

2. SAMPLES

We used two samples to generate the TLF: an FUV-selected sample (the FUVS) and an FIR-selected sample (the FIRS). The FUVS consists of a primary FUV-selected sample and a matched IRAS FIR cosample. The FIRS consists of a primary FIR-selected sample and a GALEX FUV-selected matched cosample. We measured aperture fluxes for all cosample matches using optical catalog ellipses. A small fraction of each cosample are formally nondetections—the effect of including these (negligible) is discussed in § 3.

The FUVS was generated using GALEX All-sky Imaging Survey (AIS) and Medium Imaging Survey (MIS) data (Martin et al. 2005; Morrissey et al. 2005). The sample consists of objects in GALEX internal release IR0.2 (consisting of 649 AIS and 94 MIS pointings) with FUV magnitudes brighter than 17 that have a catalog entry in the NASA/IPAC Extragalactic Database (NED). The FUV magnitude limit was selected to ensure that if the galaxy was not detected in the FIR, an IRAS...
L60  MARTIN ET AL.  Vol. 619

SCANPI (Helou et al. 1988; IRAS Explanatory Supplement 1988) upper limit (\(\sim 0.1\) Jy) would be meaningful. NED was used to determine the galaxy redshift and size. An elliptical aperture based on the galaxy size (usually from the RC3 [de Vaucouleurs et al. 1991]) was used to determine the FUV magnitude, since the patchy nature of galaxies in the FUV occasionally leads to object shredding by the GALEX pipeline. We verified that the requirement for a NED entry did not compromise completeness or the FUV-selected nature of the sample. We did this using the overlap between GALEX and the Sloan Digital Sky Survey (SDSS) Second Data Release. Out of 32 objects with FUV < 17 that SDSS classified as galaxies, 31 were in NED (the other was a close degenerate star).

The IRAS 60 and 100 \(\mu\)m data for the FUVs have been compiled from the following sources, listed in order of preference: (1) the IRAS Bright Galaxy Sample (Soifer et al. 1989), (2) the Large Optical Galaxies catalog (Rice et al. 1988), (3) the Faint Source Catalog (Moshir et al. 1992), and (4) SCANPI (version 2.4). Of the 220 galaxies, 83 had no published IRAS fluxes. Detections \(\geq 3\sigma\) were extracted from SCANPI processing for 37 of the 83. The remaining 46 are 3 \(\sigma\) upper limits (all are above 0.1 Jy) as measured from the SCANPI processing. With regard to SCANPI, the median co-added scan flux values are always used. We assume that all are extended sources.

The FIRS was generated using the PSCz survey for the primary catalog (Saunders et al. 2000). GALEX FUV data from the AIS were available (as of 2004 April 8) for 3938 deg\(^2\) of the all-sky PSCz catalog. In the overlap area, 991 galaxies appear in the PSCz catalog, with 878 having valid redshift and FUV data, for a completeness of 89\%. This small incompleteness is unlikely to affect the results. Two methods were used to correct for shredding of large galaxies, both using the APM ellipse parameters (Maddox et al. 1990; Saunders et al. 1990), which are based on second-moment fitting and are scaled to equal the APM detection isophotal area (24 mag arcsec\(^{-2}\) for O plates and 23 mag arcsec\(^{-2}\) for E plates). In the first method, all GALEX catalog objects found within the optical APM ellipse were summed to produce a total magnitude. In the second, an aperture magnitude was obtained within the APM ellipse multiplied by 2. The latter also provides FUV fluxes for PSCz objects with no GALEX-detected FUV counterpart (112 out of 878 objects). As we discuss below, including these nondetections (our default) does not affect the results.

3. LUMINOSITY FUNCTIONS

We calculate the bivariate and total luminosity functions using the \(1/V_{\text{max}}\) weighting method (Schmidt 1968). \(V_{\text{max}}\) is calculated for each object (Willmer 1997) and for the FUV and the FIR limits of the sample. For the FUV limits, we account for the field exposure time and local extinction (standard GALEX catalog value). A higher extinction reduces \(V_{\text{max}}\) (FUV).

The adopted \(V_{\text{max}}\) depends on the treatment of nondetections. For both the FIRS and the FUVS, we created samples that excluded the nondetections and included them. When excluding nondetections, we use \(V_{\text{max}} = \min [V_{\text{max}}\text{(FUV)}, V_{\text{max}}\text{(FIR)}]\), since an object can only be detected in both samples if it falls within both volumes. When including nondetections, all sources are formally included with flux estimates obtained in an identical fashion to true detections. In this case, \(V_{\text{max}}\) for the cosample is formally infinite. For the FUVS, \(V_{\text{max}} = V_{\text{max}}\text{(FUV)}\), and for the FIRS, \(V_{\text{max}} = V_{\text{max}}\text{(FIR)}\). Finally, both the BVLF and the TLF are obtained by summing \(1/V_{\text{max}}\) into logarithmic luminosity bins, with \(\Delta \log L = 0.5\).

For simplicity in this preliminary study, luminosities are defined as follows: \(L_{\text{FUV}} = L_{\text{FUV},V}L_{\text{FUV},V} \times L_{\text{FUV},V}L_{\text{FUV},V}\), where \(L_{\text{FUV},V}\) is the monochromatic FUV luminosity; and \(L_{\text{FIR}} = \rho_0L_{\text{FIR},V}L_{\text{FIR},V}\), where \(L_{\text{FIR},V}\) is the monochromatic luminosity at 60 \(\mu\)m. The total luminosity is defined as \(L_{\text{tot}} = L_{\text{FUV}} + L_{\text{FIR}}\) and converted to star formation rate using \(SFR (M_\odot \text{yr}^{-1}) = 3.5 \times 10^3L_{\text{FIR}}\) (Kennicutt 1998).

More complex relations (e.g., \(L_{\text{FIR}} = 0.65\rho_0L_{\text{FIR},V} + 0.42\rho_0L_{\text{FIR},V}\)) produce similar results but with more dispersion with respect to the simple functional fits discussed below. We make no k-corrections, as the redshifts are quite low (\(z \leq 0.04\)).

The TLF has been calculated for the FUVs (168 objects including nondetections, 136 excluding them), the FIRS (878 objects including nondetections, 766 otherwise), and a combined sample. We find that the results do not depend on the inclusion of nondetections, so all results we present include them. If all three samples include representative galaxies present in the local universe, the derived luminosity functions should be consistent within errors from sampling and cosmic variance. The combined sample is generated following the “incoherent combination” method of Avni & Bahcall (1980). The FUVS is obtained in a subset of regions covered by the FIRS. Thus the FUVS adds information only for objects that have \(f_{60} < 0.6\), the PSCz 60 \(\mu\)m limit. The combined sample therefore consists of the FIRS sample plus the FUVS (\(f_{60} < 0.6\)) subsample (113), for a total of 991 objects.

The three TLFs are displayed in Figure 1. As hoped, the three samples give quite consistent results. The FUVs slightly exceeds the FIRS at lower luminosities, while the FIRS fills out the high-luminosity end not represented in the (fairly) bright-cutoff FUVS. We restrict our analysis here to the combined sample. The error bars are generated using a bootstrap method.

As is apparent in Figure 1, a Schechter function provides a
very poor fit to the higher luminosity portion of the TLF giving a total \( \chi^2 = 115 \) for 9 degrees of freedom. On the other hand, a log normal function

\[
\phi(L) d\log L = \frac{\phi_s}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(\log(\frac{L}{L_s}))^2}{2\sigma^2}\right) d\log L \tag{1}
\]

(Saunders et al. 1990) provides a remarkably good fit. In this case, the parameters \( \phi_s = 0.150 \pm 0.035 \), \( \log L_s = 7.43 \pm 0.17 \), and \( \sigma = 0.87 \pm 0.03 \) (errors generated by the bootstrap) yield a total \( \chi^2 = 8 \) for 9 degrees of freedom.

The luminosity distribution \( L\phi(L) \) is also lognormal, peaking at \( L_s = L_s + \sigma^2 \ln 10 \), or \( L_s = 9.37 \), as we show in the inset of Figure 1. It can be seen that 50% of the SFR density comes from galaxies with \( \log L_{tot} < 9.4 \), or about \( 1 M_\odot \) yr\(^{-1}\).

We have estimated the BVLF using the combined sample, and we show a two-dimensional histogram normalized by the TLF in Figure 2a. The histogram shows quite dramatically why the local FUV luminosity function is well fitted by a Schechter function (Wyder et al. 2005; Treyer et al. 2005): the FUV luminosity appears to “saturate” at \( L_{FUV} > 10^{10} L_\odot \), with all increase in the total luminosity coming from FIR radiation. This saturation apparently occurs at higher redshift, but at an \( L_{FUV} \) that is a factor of 20 higher for \( z = 3 \) (Adelberger & Steidel 2000). For \( L_{FUV} < 10^{10} L_\odot \) the FIR and FUV luminosities track, but with a slope steeper than unity. There appears to be a trough between these regions. The trough is statistically significant, as it falls in the range in which the object number distribution peaks.

In Figure 2b, we show the BVLF rebinned in logarithmic \( L_{tot} \) and \( L_{FUV}/L_{FIR} \) bins. The total luminosity is well correlated with the FIR-to-UV ratio, and a line is shown with the fit \( L_{tot} = 9.4 + 1.3 \log (L_{FIR}/L_{FUV}) - 0.15(\log (L_{FIR}/L_{FUV}))^2 \). The trend of increasing \( L_{FIR}/L_{FUV} \) with increasing \( L_{tot} \) was first noted by Wang & Heckman (1996). Note also that the FUV projection of the BVLF for the FUVS sample is in excellent agreement with Wyder et al. (2005).

We use the BVLF to calculate the luminosity density using a simple sum: \( \rho = \int L\phi(L_{FUV}, L_{FIR}) d\log L_{FUV} d\log L_{FIR} \). From the inset in Figure 1, it is apparent that extrapolation to low or high luminosity using a model fit to calculate the luminosity density would not alter this result greatly. The results, using the Kennicutt (1998) SFR conversion factor, are \( (L_{FUV}, L_{FIR}, L_{opt}) = (0.010 \pm 0.0014, 0.011 \pm 0.0005, 0.021 \pm 0.0019) M_\odot \) yr\(^{-1}\) Mpc\(^{-3}\). Hence the luminosity density is split roughly 50-50 into primary FUV and reprocessed FIR light.

4. Discussion

We have made the first attempt at deriving the bivariate luminosity function for the two bands that trace the high-mass star formation rate in galaxies. The BVLF can be derived from FUV, FIR, or combined samples. The resulting functions agree for the samples we studied, as hoped. Large, homogeneous, combined samples that probe the bulk of the BVLF will provide an excellent tool for studying the relationship between FUV and FIR emission.

We have used the BVLF to generate a total high-mass star formation luminosity function and luminosity density for the local universe. Our value for the SFR density, \( 0.021 M_\odot \) yr\(^{-1}\) Mpc\(^{-3}\) (\( z = 0.02 \)), is in good agreement with the estimate of Pérez-González et al. (2003), using extinction-corrected H\(\alpha\) of \( 0.025 M_\odot \) yr\(^{-1}\) Mpc\(^{-3}\) and that using extinction-corrected FUV from GALEX (Wyder et al. 2005), also \( 0.025 M_\odot \) yr\(^{-1}\) Mpc\(^{-3}\).

There are a number of striking features of the BVLF and TLF. We have pointed out the divergence of \( L_{FIR} \) and \( L_{FUV} \), behavior similar to that observed when comparing FIR and optical light (Saunders et al. 1990; Buat & Burgarella 1998). The BVLF has a bimodal appearance, roughly divided at \( 3 M_\odot \) yr\(^{-1}\). Perhaps below the threshold SFR, star formation
is an equilibrium process and feedback is successful at clearing sightlines for FUV emergent flux. With a very high SFR, the process may take on a nonequilibrium character, where feedback fails to (or has yet to) clear paths for primary radiation. The FIR-to-FUV flux ratio appears to be a rough total luminosity proxy. One explanation is that the highest SFRs occur in the most massive star-forming galaxies (Brinchmann et al. 2004). The most massive galaxies are the most metal-rich (Tremonti et al. 2004), and a high-metallicity interstellar medium (ISM) has a high gas-to-dust ratio. Also, the highest SFRs appear to occur in galaxies with the highest ISM surface mass densities (Kennicutt 1989) and higher dust column density.

It has also been known for some time that the FIR luminosity function is not a Schechter function (Saunders et al. 1990), whereas we now know from GALEX that the UV luminosity function is (Wyder et al. 2005). Taken together with the diversity of star formation modalities making up our sample, it is therefore surprising to learn how well the total luminosity function is described by a single lognormal function over 5 decades of luminosity. Norman et al. (2004) found a lognormal distribution for the X-ray luminosity function and note that it is the expected distribution for a complex multiplicative random process. Perhaps a unifying physical framework can be found for star formation in galaxies ranging from irregular dwarfs to ultraluminous merging galaxies.

Optical and near-infrared luminosity functions, which trace stellar mass, are well fitted by Schechter functions (Bell et al. 2003), as is the UV luminosity function. The fact that the TLF is so distinct from that of the fuel, HI (Zwaan et al. 2003) and CO (Keres et al. 2003), which are also well fitted by Schechter functions (Bell et al. 2003), as is the UV luminosity function. The fact that the TLF evolves over cosmic time. Lyman break galaxies show rest-frame FUV well fitted by Schechter functions, but with a characteristic UV luminosity a factor of 20 larger. While there is no question that luminous star-forming galaxies were more pervasive in the past, a major question in extragalactic astronomy remains the relationship between galaxies selected by rest UV versus rest FIR. Our work suggests that with the launch of GALEX and the Spitzer Space Telescope, and the flowering of submillimeter astronomy, a unified approach to combining rest FUV and FIR information will bring major insights in the next few years.

GALEX is a NASA Small Explorer, launched in 2003 April. We gratefully acknowledge NASA’s support for construction, operation, and science analysis for the GALEX mission, developed in corporation with the Centre National d’Etudes Spatiales of France and the Korean Ministry of Science and Technology. The grating, window, and aspheric corrector were supplied by France. We also acknowledge valuable comments from the referee. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Adelberger, K. L., & Steidel, C. C. 2000, ApJ, 544, 218
Avni, Y., & Bahcall, J. N. 1980, ApJ, 235, 694
Bell, E. F., McIntosh, D. H., Katz, N., & Weinberg, M. D. 2003, ApJS, 149, 289
Brinchmann, J., Charlot, S., White, S. D. M., Tremonti, C., Kauffmann, G., Heckman, T., & Brinkmann, J. 2004, MNRAS, 351, 1151
Buat, V., & Burgarella, D. 1998, A&A, 334, 772
Buat, V., et al. 2005, ApJ, 619, L51
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R. J., Paturel, G., & Fouqué, P. 1991, Third Reference Catalogue of Bright Galaxies (Berlin: Springer)
Fall, S. M., Charlot, S., & Pei, Y. C. 1996, ApJ, 464, L43
Hehou, G., Khan, I. R., Malek, L., & Bohmer, L. 1988, ApJS, 68, 151
IRAS Catalogs and Atlases: Explanatory Supplement. 1988, ed. C. A. Beichman, G. Neugebauer, H. J. Habing, P. E. Clegg, & T. J. Chester (Washington, DC: GPO)
Kennicutt, R. C., Jr. 1989, ApJ, 344, 685
———. 1998, ARA&A, 36, 189
Keres, D., Yun, M. S., & Young, J. S. 2003, ApJ, 582, 659
Madau, P., Ferguson, H. C., Dickinson, M. E., Giavalisco, M., Steidel, C. C., & Fruchter, A. 1996, MNRAS, 283, 1388
Maddox, S. J., Sutherland, W. J., Efstathiou, G., & Loveday, J. 1990, MNRAS, 243, 692
Martin, D. C., et al. 2005, ApJ, 619, L1
Moshir, M., et al. 1992, Explanatory Supplement to the IRAS Faint Source Survey, Version 2 (Pasadena: JPL)
Morrisey, P., et al. 2005, ApJ, 619, L7
Norman, C., et al. 2004, ApJ, 607, 721
Pérez-González, P. G., Gallego, J., Zamorano, J., Alonso-Herrero, A., Gil de Paz, A., & Aragón-Salamanca, A. 2003, ApJ, 587, L27
Rice, W., Lonsdale, C. J., Soifer, B. T., Neugebauer, G., Kopan, E. L., Lloyd, L. A., de Jong, T., & Habing, H. J. 1988, ApJS, 68, 91
Saunders, W., Rowan-Robinson, M., Lawrence, A., Efstathiou, G., Kaiser, N., Ellis, R. S., & Frenk, C. S. 1990, MNRAS, 242, 318
Saunders, W., et al. 2000, MNRAS, 317, 55
Schmidt, M. 1968, ApJ, 151, 393
Soifer, B. T., Boehmer, L., Neugebauer, G., & Sanders, D. B. 1989, AJ, 98, 766 (erratum 99, 432)
Tremonti, C., et al. 2004, ApJ, 613, 898
Treyer, M., et al. 2005, ApJ, 619, L19
Wang, B., & Heckman, T. M. 1996, ApJ, 457, 645
Willmer, C. N. A. 1997, AJ, 114, 898
Wyder, T., et al. 2005, ApJ, 619, L15
Zwaan, M. A., et al. 2003, AJ, 125, 2842