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Measuring Star Formation in Local and Distant Galaxies

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Summary. — I review measurements of star formation in nearby galaxies in the UV–to–FIR wavelength range, and discuss their impact on SFR determinations in intermediate and high redshift galaxy populations. Existing and upcoming facilities will enable precise cross-calibrations among the various indicators, thus bringing them onto a common scale.

PACS `95.85.-e` – Astronomical Observations; Multiwavelength.
PACS `98.52.Nr` – Spiral Galaxies.
PACS `98.52.Sw` – Irregular and Morphologically Peculiar Galaxies.
PACS `98.54.Ep` – Starburst Galaxies.

1. – Introduction

Determinations of star formation rates (SFRs) in galaxies utilize indicators at a variety of wavelengths, from the X–ray to the radio. Many indicators have been defined in response to specific needs. For instance, when new populations of galaxies are discovered using a new wavelength window or improved observing techniques/instruments in a certain waveband, there is a push to investigate whether that waveband can be used to derive SFRs as well, and/or to define the uncertainties and limitations of doing so.

The advent of new facilities (e.g., Herschel, LMT, ALMA, JWST, etc., and the many ground–based telescopes under construction or design) together with existing ones (HST, Spitzer, Chandra, and the vast array of existing ground–based facilities) will cover extensively the electromagnetic spectrum at unprecedented sensitivities. This will offer the opportunity to cross-calibrate many of the SFR indicators across a range of redshifts, and, therefore, on many galaxy populations at various stages of their evolution.

In this brief review, I discuss the current status and the known limitations of SFR indicators in a few wavelength regimes: ultraviolet (UV), optical/near–infrared, and mid/far–Infrared (MIR/FIR).

2. – General Assumptions and Limitations

By definition, most SFR indicators probe the *massive stars formation rate*; their scope is to measure the instantaneous or recent SFR of a galaxy or system (as opposed to the

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time–averaged SFR). Thus, the measured luminosity L(λ) needs an assumption on the stellar Initial Mass Function (IMF) to be converted to an actual SFR. All indicators are insensitive to the low-end of the stellar IMF, which thus remains a free parameter (or an uncertainty) for all such measures. The sensitivity to the high–end of the IMF varies from indicator to indicator (as we will see in the next sections), which thus complicates comparisons among different indicators. The issue of the form and mass limits of the stellar IMF will not be discussed here, but needs to be kept in mind when deriving SFRs from any luminosity measurement.

Another factor to account for is the impact of dust on the luminosity L(λ) of a galaxy. UV, optical, and near–infrared luminosities probe the stellar light that emerges from galaxies unabsorbed by dust; thus, for these wavelengths, the main problem is to correct the observed luminosities for the effects of dust attenuation. Infrared luminosities measure the stellar light that has been reprocessed by dust and emerges beyond a few μm. In this case, the main problem is to establish whether the re-processed light comes from young, massive stars (associated with the current star formation) or from older stellar populations.

In general, L(λ) is the sum of the contributions from all its stellar populations (or from the dust re-processed light of all populations). Thus, deriving a SFR from L(λ) implies quantifying the impact, if any, of any stellar population that is contributing to L(λ), but is not part of the current star formation event. Specific examples include evolved (aged) stellar populations. Added to this is the well–known age–dust degeneracy, for which a young, dusty population observed at UV–optical wavelengths can mimic the colors of an old, dustless population.

3. – SFR(UV)

The ultraviolet (λ ∼912–3000 Å) probes directly the bulk emission from the young, massive stars, thus could be considered the SFR indicator *par excellence*. Ease of access of the restframe UV emission (redshifted into the optical bands) for high redshift galaxies [27, 39, 14, 4] has sparkled, over the past dozen of years or so, extensive investigations on its use and limitations as a SFR estimate [19, 36].

However, a number of effects limit the use of SFR(UV), unless those effects are properly treated. The UV is heavily impacted by dust attenuation: A_V=1 mag implies $A_{1500\mathring{A}}$ ≈3 mag, and the exact value depends on the details of the dust geometry in the galaxy. The star formation history of a galaxy also determines its UV luminosity: a system which has been forming stars at a constant level of 1 $M_\odot$ yr^{-1} over the past 100 Myr is indistinguishable from an instantaneous 4×10^8 $M_\odot$ burst of star formation which has been passively evolving for the past 50 Myr. Indeed, the UV probes star formation over the timescale in which stars are bright in the non–ionizing UV wavelength range, of–order 100 Myr. The age–dust degeneracy is potentially a problem when observing the UV colors of galaxies, as a 10^6 $M_\odot$, 300 Myr old burst has a UV spectral slope that is virtually indistinguishable from that of a constant star formation system forming stars at a rate of 1 $M_\odot$ yr^{-1} and reddened by a color excess of E(B−V)=0.4 (although the latter is about 200 times brighter than the former at 1500 Å, according to the Starburst99 models [25]).

Despite all the problems listed above, starburst galaxies follow a well defined relation between dust reddening and dust attenuation [28, 7], in the sense that a measurement of UV slope or colors can be effectively used to derive the total amount of dust opacity affecting the system [11]. Here starbursts are defined as systems with specific SFRs (i.e., SFR/area): Σ_{SFR} >0.3–1 $M_\odot$ yr^{-1} kpc^{-2}. The relation between dust reddening and attenuation in starbursts has a relatively small dispersion around the mean trend (about a factor 2, Figure 1), and has been effectively used to recover the intrinsic UV emission of strongly star–forming systems at high redshift, such as Lyman Break Galaxies [39, 14].

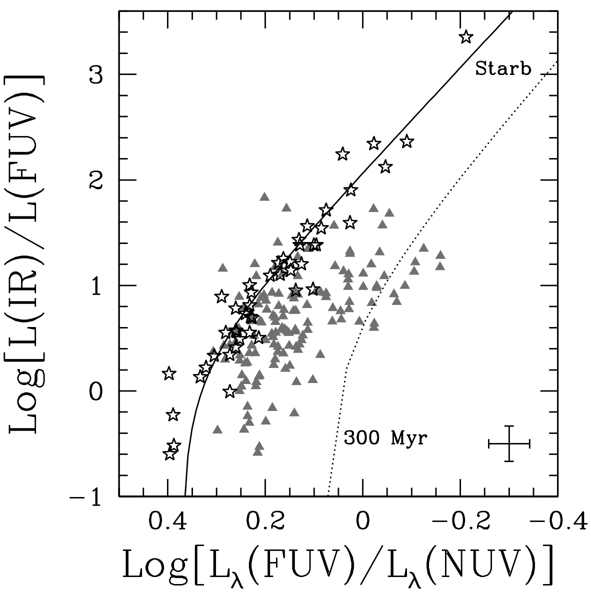

Fig. 1. – The FIR/UV ratio (the ratio of the far–infrared to the far–UV luminosity, a measure of dust attenuation) versus the UV color (given here as the ratio between the GALEX far–UV and near–UV fluxes, a measure of dust reddening) for starburst galaxies and quiescently star–forming regions. Starburst galaxies are shown as star symbols and star–forming regions within the galaxy NGC5194 [9] are shown as grey filled triangles. Redder UV colors (more dust reddening) correspond on average to larger FIR/UV ratios (larger dust attenuation). The continuous line shows the best fit to the starburst galaxies, which is also the locus of a progressively more attenuated (from left to right) constant star–forming population. The dotted line shows the same dust attenuation trend for a 300 Myr old stellar population, which represents a lower envelope to the NGC5194 star–forming regions.

Deviations from the well-behaved starburst attenuation–reddening relation have been observed, however, for other galaxy populations. Ultraluminous Infrared galaxies, for instance, show an excess attenuation for the measured UV reddening [15], likely due to the higher dust opacities affecting those systems. Quiescently star–forming galaxies and regions (systems with $\Sigma_{SFR} \ll 0.3$ $M_\odot$ yr^{-1} kpc^{-2}) show a ten times larger spread in the dust attenuation at fixed UV reddening relative to starbursts (Figure 1); the sequence for starburst galaxies forms the upper envelope to the distribution of the quiescently star–forming systems [5, 1, 16, 22, 37, 9]. The behavior of the quiescently star–forming systems is explained if the observed UV colors are not only a probe of dust reddening, but also of age reddening, due to contribution to the UV from aged (non–star–forming) stellar populations. This adds a second parameter that complicates the definition of SFR(UV) for these systems.

4. – SFR(Optical) and SFR(near–infrared)

At optical and near–infrared wavelengths, the continuum stellar emission is the result of the contributions from stellar populations born throughout the entire history of the galaxy. Thus, indicators of current/recent SFR cannot use continuum measurements. They instead rely on ionizing photon tracers [20, 13, 21, 29]: the multitude of hydrogen recombination lines (most often Hα, Hβ, Pβ, Pα, Brγ) and of forbidden lines (chiefly [OII] and [OIII]). These, thus, trace the most massive, ionizing stars, and timescales of about 10 Myr, i.e. the most recent events of star formation in the galaxy.

Line emission SFR indicators are more sensitive to variations of the upper end of the stellar IMF than SFR(UV). For comparison, a change of a factor 3 in the upper mass value of the IMF changes the calibration of SFR(line) by twice as much as SFR(UV). Hydrogen recombination lines also need to be corrected for underlying stellar absorption [33], and metallicity and ionization conditions need to be taken into account for metal forbidden lines [29].

Dust extinction affects most the bluer lines: for instance neglecting extinction corrections in a generic sample of nearby galaxies will yield about a factor 3 underestimate in the SFR from Hα [33]. Furthermore, the underestimate will be higher for brighter galaxies, because of the extinction–SFR correlation [6]. Near–infrared hydrogen recombination lines (Pβ, Pα, Brγ) would then appear to be an obvious choice for determining SFRs of galaxies. For example, a visual extinction A_V=5 mag (a factor 100, typical of the central regions of spiral galaxies) is reduced to $A_{P\alpha}$=0.7 mag (or a factor 2). However, observational limitations of ground–based telescopes, specifically the high atmospheric background, have so far confined the use of Pβ(1.28 μm) and Brγ(2.16 μm) to the brightest regions of galaxies (Pα(1.88 μm) lies in a wavelength region where the atmospheric transmission is very low and variable, thus it is virtually inaccessible from the ground).

From space the background in the H–band is about 800 times lower than from the ground, implying higher sensitivities, and lines like Pα become accessible. Pα is preferable over Pβ and Brγ, because it is 3 and 10 times stronger, respectively. In addition, unlike Pβ, it is unaffected by neighboring contaminating lines and is about a factor of 2 less sensitive to dust extinction. Current (NICMOS) and upcoming (WFC3) instruments on HST can access low–redshift Pα and Pβ, but the small field–of–view inhibits observations of large or complete samples of galaxies. Future facilities like NIRSpec on JWST can access Pα in galaxies up to redshift $\sim$1.5, i.e., roughly up to the peak of the cosmic SFR [17], and, according to models, at the peak of the dust opacity as well [31, 8]. This, in turn, calls for a term of comparison at z=0, i.e., for large samples of nearby galaxies observed in Pα, which can them be directly compared to the higher redshift observations.

For an extinction–corrected hydrogen line luminosity, the calibration to SFR is given by:

$$SFR(M_\odot\ yr^{-1}) = 5.3\times10^{-42}L(H\alpha)(erg\ s^{-1}) = 4.2\times10^{-41}L(P\alpha)(erg\ s^{-1}), \tag{1}$$

for an IMF consisting of two power laws: slope -1.3 in the range 0.1–0.5 $M_\odot$ and slope -2.3 in the range 0.5–120 $M_\odot$ [23].

5. – SFR(MIR) and SFR(FIR)

The Spitzer Space Telescope has recently enabled the investigation of the mid–infrared emission ($\lambda\sim$5–40 μm) as a SFR indicator, thus expanding on the work pioneered by

ISO [34, 12, 2]. The interest in the MIR region stems from the consideration that the dust heated by hot, massive stars can have high temperatures and will thus emit at short infrared wavelengths. The MIR continuum is due to dust heated by a combination of single–photon and thermal equilibrium processes, with the latter becoming more and more prevalent over the former at longer wavelengths. The MIR bands are generally attributed to Polycyclic Aromatic Hydrocarbons [24, 38], large molecules transiently heated by single UV and optical photons in the general radiation field of galaxies or near B stars [30], and which can be destroyed, fragmented, or ionized by harsh UV photon fields [3, 32].

An analysis of the 24 μm (Spitzer/MIPS 24 μm band) emission from nearby star–forming regions and starburst galaxies shows that this band is a good SFR tracer, in the absence of AGNs [10]. A calibration can be provided, over a luminosity range of >3.5 dex:

$$SFR(M_\odot\ yr^{-1}) = 1.24 \times 10^{-38}[L(24\ \mu m)\ (erg\ s^{-1})]^{0.88}. \tag{2}$$

An even better SFR tracer can be provided by combining the 24 μm luminosity (which probes the dust–absorbed star formation) and the *observed* Hα luminosity (which probes the unobscured star formation):

$$SFR(M_\odot\ yr^{-1}) = 5.3 \times 10^{-42}[L(H\alpha)_{obs} + (0.031 \pm 0.006)L(24\ \mu m)]. \tag{3}$$

The 8 μm emission from the same star–forming regions and starburst galaxies is, instead, dependent on both metallicity and star formation history, to a level that it is unclear whether it can be effectively used as a SFR indicator for a generic galaxy population (unless the basic characteristics of this population are known).

SFR(FIR)($\lambda \sim$5–1000 μm) has been calibrated since the times of the IRAS satellite, under the baseline assumption that, at least locally, young star–forming regions are dusty and the dust absorption cross–section peaks in the UV, i.e., in the same wavelength region where young, massive stars emission also peaks. This assumption, however, has been known to be approximate for at least as long [18, 26, 35]. The first approximation is related to the opacity of a galaxy: not all the luminous energy produced by recently formed stars is re-processed by dust in the infrared; in this case, the FIR only recovers part of the SFR, and the fraction recovered depends, at least partially, on the amount of dust in the system. The second approximation is related to the heating of the dust by evolved, non–star forming population: these will also contribute to the FIR emission, providing an excess to SFR(FIR). If more evolved populations contribute mainly to the longer wavelength FIR, this extra contribution may be calibrated, at least for some classes of galaxies. Many project on the upcoming Herschel telescope will be devoted to the investigation of the evolved stars contribution to the FIR emission of galaxies. One of the extant questions is whether the peak of the FIR emission (located in the wavelength range 70–100 μm) can be used as a reliable tracer of current SFR, and what limitations to its applicability may come from contamination of evolved populations.

* * *

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