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Extragalactic star formation rate – estimates at different wavelengths

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Abstract. The star formation rate (SFR) in galaxies is of prime importance in the study of formation and evolution of galaxies. Different methods have hence been evolved to estimate the current SFR in galaxies, using indicators at different wavelengths. These methods are reviewed briefly. While there is a good correlation between different estimators, one needs to exercise caution while applying any single method to an individual galaxy,or more particularly, an individual star forming region. However, the availability of data at several wavelengths helps in understanding the environments of different types of galaxies, and an individual starforming region better.

Keywords : stars: formation – galaxies: stellar content

1. Introduction

Star formation is central to the understanding of formation and evolution of galaxies as also the origin of the Hubble sequence. Considerable effort is hence invested towards investigations of the triggers that lead to the collapse of gas into stars, the rate of star formation, and the mass spectrum of the stars formed. While young open star clusters in our Galaxy provide an opportunity to count the stars of different masses that helps in an accurate estimate of star formation rate (SFR) as well as the initial mass function (IMF) of stars formed, stars cannot be resolved in all but the nearest galaxies. The young clusters in regions of enhanced star formation are most often comparable to globular clusters in size, for which there is no young analogue in our Galaxy. While modelling their integrated light provides some clues to the stellar population, the background of older stars requires to be removed effectively. On the other hand, many indirect measures are available, primarily related to the light emitted by

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massive stars, or based on the energetic particles injected by them into the interstellar medium near the end state of their evolution. While these methods have proved highly useful in estimating the total SFR in a majority of galaxies, there are uncertainties in the case of extreme galaxies and individual star forming regions. In such cases, one needs to keep in mind the fundamental assumptions made in arriving at the estimates while applying different methods, and use the differences in estimates made at different wavelengths as clues to the nature of the enivronment and processes leading to star formation. We introduce the different methods of estimation of SFR in this brief review.

The high mass stars are shortlived and hence an estimate of a number of such stars will be directly proportional to the current SFR within the uncertainties of IMF. Their total radiation can be estimated from stellar population synthesis models, which are somewhat sensitive to the metallicity of the stars. The radiation is absorbed and reprocessed at different wavelengths, and certain amount of modelling is required for estimating SFR from the observed diagnostics. There is an extensive literature on this topic, but we include a few recent works in this review and refer the reader for the extensive reviews by Condon (1992) and Kennicutt (1998) for further details and early literature. The calibrations have been improved continously since these early reviews. The STARBURST99 (Leitherer et al. 1999) models are often used in the calibrations. An improved IMF by Kroupa (2001) is gaining popularity over the widely used Salpeter IMF. Murphy et al. (2011) have improved several calibrations recently, in an attempt to use the multiwavelength data to understand the star formation in individual regions of NGC 6946, a nearby late type spiral with mild starburst nucleus.

2. Stellar population synthesis

Since the stellar population of distant galaxies is unresolved, comparing their spectra (or colours to a lesser accuracy) with synthetic population models provides a way to estimate the amount of young stellar population. The models may use a spectral library of stars of different spectral types, luminosities, ages and metallicities, or more simply, use theoretical spectra and stellar evolutionary models. Larson & Tinsley (1978) summarize early attempts in this direction, but warn of systematic errors due to incorrect IMF, age, metallicities and reddening. However, the method has evolved significantly in recent years, and has been used especially to separate intermediate populations of age < 1 Gyr from the old > 4 Gyr population. Since our interest is in the current SFR, we will not review this area in detail, but only mention the work Ramya, Sahu & Prabhu (2009) which used the STARBURST99 models to obtain evidence for the young population superposed on old and intermediate age populations in several blue compact dwarf (BCD) galaxies. An estimate of relative contributions of different populations to the integrated light could be arrived at.

3. Far-ultraviolet radiation

Massive stars are hot and emit a copious amount of ultraviolet (UV) radiation. The radiation shortward of Lyman continuum is almost fully absorbed by the surrounding gas. Dust absorbs the radiation longwards of the limit, and the reprocessed radiation provides us with an estimate of the ultraviolet radiation. This will be discussed in Section 6.

Space-based telescopes provide us with an opportunity to measure the radiation in the range 1200-3000Å. *GALEX* uses two bands: FUV (1400-1650Å) and NUV(2000-2500Å). Both these bands provide a direct estimate of SFR without contamination by older stars, through a comparison with the modelled radiation from massive stars. For Kroupa IMF, and continuous star formation models of STARBURST99 one obtains (Kennicutt et al. 2009),

$$\mathrm{SFR}\ (M_\odot\ \mathrm{yr}^{-1}) = 8.8 \times 10^{-29} L_\nu\ \mathrm{erg\ s^{-1}\ Hz^{-1}}. \tag{1}$$

Murphy et al. (2011) derive the following relation for integrated flux in *GALEX* FUV band:

$$\mathrm{SFR}\ (M_\odot\ \mathrm{yr}^{-1}) = 4.42 \times 10^{-44} L_{\mathrm{FUV}}\ \mathrm{erg\ s^{-1}}. \tag{2}$$

The interstellar attenuation is very high in this region of spectrum, which adds considerable uncertainty (Bell 2003). Hybrid indicators described in Section 10 attempt to account for dust attenuation from the thermal infra-red observations.

4. Recombination lines

The UV radiation from hot stars, shortward of Lyman limit, ionizes the surrounding gas to produce an ionized hydrogen region. This H II region is often, but not always, ionization bounded with neutral gas extending outside. The ionized gas recombines, producing emission lines. Under the assumption of equilibrium between ionization and recombination, the recombination line fluxes provide an estimate of ionizing radiation. The Balmer lines, particularly Hα, are generally used to estimate the star formation, and similar estimates can be obtained from the Paschen, Brackett, and radio recombination lines. Murphy et al. (2011) provide the following calibration for Hα assuming Case B recombination at T_e = 10000 K:

$$\begin{aligned}\mathrm{SFR}\ (M_\odot\ \mathrm{yr}^{-1}) &= 5.37 \times 10^{-42} L(\mathrm{H}\alpha)(\mathrm{erg\ s^{-1}}) \\ &= 7.29 \times 10^{-54} Q(\mathrm{H}^0)(\mathrm{s}^{-1}),\end{aligned} \tag{3}$$

where $Q(\mathrm{H}^0)$ is the number of photons shortward of Lyman limit emitted by stars per second.

The assumption of IMF, and adopted stellar evolution and atmospheric models results in 30% dispersion in the calibration. Extinction by dust may introduce a greater uncertainty, and hence the infrared lines are preferred, though fainter. Dust mixed with gas in the ionized region absorbs some of the ionizing radiation too, which needs to be estimated. If the parent cloud of star-forming region is density bounded and cannot absorb all the ionizing radiation, the radiation leaks out and ionizes the diffuse matter outside. One needs to account for the leakage known as escape fraction. If SFR is measured over the entire galaxy, one needs to account for only the leakage into intergalactic matter; this may not be severe, except for extreme starbursts, and dwarf starforming galaxies with small thickness of gaseous disk.

Radio recombination lines require powerful radio telescopes and pioneering work was undertaken by Anantharamaiah and collaborators with the VLA (see *e.g.*, Kepley et al. 2011)). The thermal radio continuum emission can also be similarly calibrated (see Section 7).

5. Forbidden lines

The forbidden lines arise due to collisional excitation to, and radiative de-excitation from, the metastable levels of heavier elements. These lines cool the H II regions to an equilibrium temperature that ranges from about 8000 K to 12000 K, reducing with metallicity. Neutral, singly or doubly ionized oxygen is a common example in the optical region. Fluxes in these lines in an H II region can be modeled under the assumption of ionization bounded nebula with known electron density and temperature. In the case of galaxies where the Hα line is redshifted beyond the optical region, the strong line of [O II]λ3727 appears a good alternative to estimate the SFR (Moustakas & Kennicutt 2006). Though the forbidden line fluxes depend not only on the ionizing flux, but also on the abundances and ionization state of the nebula, the [O II] line is reasonably well-behaved, and one obtains the calibration (Kennicutt 1998),

$$\mathrm{SFR}\ (M_\odot\ \mathrm{yr}^{-1}) = (1.4 \pm 0.4) \times 10^{-41} L([\mathrm{O\,II}])(\mathrm{erg\ s}^{-1}). \tag{4}$$

A more detailed treatment can be found in Moustakas, Kennicutt & Tremonti (2006).

Recently Kennicutt (1998) calibrated the far-infrared line of [C II]157.74μm line, which is an important coolant in H II regions and hence very bright.

6. Far-infrared radiation

Star-forming regions are dusty, and the stellar radiation absorbed by dust heats the dust grains which re-emit in the thermal infrared. Equilibrium temperature of dust grains depends on their size. Smaller grains get hotter and emit in the mid-infrared, whereas larger ones in the far-infrared (FIR: 40-200 μm). Kennicutt (1998) has argued that 8-1000 μm (which we refer as thermal-IR or TIR since it includes mid-IR as well as FIR) integrated luminosity would provide very good estimate of SFR for regions with age less than 10^8 years, and provides the following calibration:

$$\mathrm{SFR}\ (M_\odot\ \mathrm{yr}^{-1}) = 4.5 \times 10^{-44} L_{\mathrm{TIR}} (\mathrm{erg\ s}^{-1}) \tag{5}$$

However, he suggests using empirical calibrations based on observations of each class of galaxies since a high optical depth would increase the theoretical calibration, while the infrared cirrus – the large scale diffuse emission due to dust heated by older stars, loose associations, radiation leaking from star forming regions, and hot dust formed in circumstellar environments – would lower it. Murphy et al. (2011) revised the calibration constant to 3.88×10^{-44}. Calibrations also exist in the literature using flux density in individual bands such as 8, 24, 160 μm. Note that 8 μm band is generally dominated by the emission by polycyclic aromatic hydrocarbons (PAH) at 7.7 μm, but it appears that the PAH emission correlates well with emission by fine dust.

7. Radio continuum

The ionized gas emits continuum radiation as well, but its amount is small in the optical-infrared region. The free-free radiation is strong in the high-frequency radio region, and can be used in a manner analogous to recombination lines to estimate SFR. However, apart from the contribution by synchrotron radiation at low frequencies, the higher frequencies may have contribution due to dust, especially the fine spinning dust which gives rise to anomalous microwave emission discovered through fluctuations in the microwave background maps. The region around 33 GHz is reasonably free of both contaminants (Peel et al. 2011). Murphy et al. (2011) provide the following calibration:

$$\mathrm{SFR}\ (M_\odot\ \mathrm{yr}^{-1}) = 4.6 \times 10^{-28} T_{\mathrm{e}}^{-0.45} \nu^{0.1} L_\nu^{\mathrm{T}} (\mathrm{erg\ s}^{-1}\ \mathrm{Hz}^{-1}), \tag{6}$$

where T_{e} is in units of 10^4 K and ν is in GHz.

The low frequency radio radiation, on the other hand, is non-thermal in origin, caused by synchrotron emission due to energetic electrons moving in the galactic magnetic field. Supernova explosions are the main sources of the high energy electrons in a star forming region. The non-thermal radio radiation thus provides a measure of massive stars which have ended their life as core collapse supernovae. This also provides an estimate of SFR under some assumptions. Condon (1992) provides an excellent review of radio emission from galaxies. Particular attention may be paid to the leakage of electrons, as well as mechanisms of energy loss of which synchrotron and inverse Compton are the most dominant at the highest energies. Supernova rate is estimated for a given IMF and SFR, and the nonthermal spectral luminosity estimated from the observations in our Galaxy. Murphy et al. (2011) derive a calibration,

$$\mathrm{SFR}\ (M_\odot\ \mathrm{yr}^{-1}) = 6.64 \times 10^{-29} \nu^{\alpha^{\mathrm{NT}}} L_\nu^{\mathrm{NT}} (\mathrm{erg\ s}^{-1}\ \mathrm{Hz}^{-1}), \tag{7}$$

where ν is in GHz and α^{NT} the nonthermal spectral index.

8. X-rays

The X-ray radiation from a star forming region is mostly accounted for by the high-mass X-ray binaries (HMXBs) which consist of a star of mass $\gtrsim 10 M_\odot$ and a compact companion (neutron star or black hole) interacting with each other. Mineo, Gilfanov & Sunyaev (2011) estimate

$$\mathrm{SFR}\ (M_\odot\ \mathrm{yr}^{-1}) = 4.0 \times 10^{-40} L(0.5 - 8keV)(\mathrm{erg\ s}^{-1}). \tag{8}$$

Zheng et al. (2011) have calibrated individually the 0.5–2 keV and 2-8 keV bands which, together, are consistent with the above calibraton.

9. Radio-IR correlation

All of the above indicators of SFR show an expected correlation. This has led to hybrid calibrations described in Section 10. We will make a special mention of radio and thermal infrared correlation here since considerable attention has been paid to this in the literature, and since this had originally driven the use of non-thermal radio emission as a star formation tracer.

The low-frequency radio radiation is nonthermal in origin, and traces the star formation indirectly through the cosmic rays generated by supernovae. The infrared radiation, on the other hand, directly measures the amount of radiation from a young starburst absorbed by dust. Both these indicators appear to estimate the SFR well for normal galaxies and hence a strong correlation is apparent between the nonthermal radio and FIR radiation. Bell (2003) has argued that both these indicators equally underestimate SFR at the low-luminosity end (due to leakage of FUV as well as particle radiation), and hence the correlation is a conspiracy (Condon 1992, see also).

An alternative means of examining the correlation is through the definition of a parameter q defined as

$$q \equiv \log\Big(\frac{\mathrm{FIR}}{3.75 \times 10^{12}\ \mathrm{W\ m}^{-2}}\Big) - \log\Big(\frac{S_\nu}{\mathrm{W\ m}^{-2}\mathrm{Hz}^{-1}}\Big). \tag{9}$$

With $\nu \sim 1.4$ GHz, $\langle q \rangle \sim 2.3$ for normal star forming galaxies without strong active nuclei.

10. Hybrid calibrations

The observed correlations between different estimators of SFR has led to the calibration of composites of two different estimators. Of these, the combination of FIR flux and an optical estimator appears most robust. The observed emission line fluxes from star forming regions are severely affected by the attenuation by dust. The attenuation is generally estimated by recombination line ratios, but would wildly vary within a galaxy, and may not always be mapped thoroughly. On the other hand, the attenuation is also a measure of the amount of dust and correlates with the FIR radiation within the uncertainties due to the optical depth of dust and contribution of infrared cirrus. Several authors have tried to evolve a calibration using the observed Hα and FIR radiation to estimate SFR ((Kennicutt et al. 2009) and references therein). We reproduce here some of the calibrations due to Kennicutt et al. (2009) for different composite estimations.

$$\mathrm{SFR}\ (M_{\odot}\ \mathrm{yr}^{-1}) = 7.9 \times 10^{-42}[L(\mathrm{H}\alpha)_{\mathrm{obs}} + (0.0020 \pm 0.0005)L(\mathrm{FIR})](\mathrm{erg\ s}^{-1}), \quad (10)$$

where $L(\textsc{h}\alpha)_{\mathrm{obs}}$ is Hα luminosity uncorrected for dust attenuation, and L(FIR) is integrated FIR luminosity. The calibration is based on the *Spitzer* Infrared Nearby Galaxies Survey (SINGS) sample of galaxies.

$$\mathrm{SFR}\ (M_{\odot}\ \mathrm{yr}^{-1}) = 7.9 \times 10^{-42}[L(\mathrm{H}\alpha)_{\mathrm{obs}} + (0.39 \pm 0.10)L_{1.4\mathrm{GHz}})](\mathrm{erg\ s}^{-1}), \quad (11)$$

using SINGS and another independent 'MK06' (Moustakas & Kennicutt 2006) sample.

$$\mathrm{SFR}\ (M_{\odot}\ \mathrm{yr}^{-1}) = 8.1 \times 10^{-42}[L([\mathrm{O\,II}])_{\mathrm{obs}} + (0.0036 \pm 0.0006)L(\mathrm{FIR})](\mathrm{erg\ s}^{-1}), \quad (12)$$

using the MK06 sample.

$$\mathrm{SFR}\ (M_{\odot}\ \mathrm{yr}^{-1}) = 7.9 \times 10^{-42}[L([\mathrm{O\,II}])_{obs} + (0.54 \pm 0.10)L_{1.4\mathrm{GHz}})](\mathrm{erg\ s}^{-1}), \quad (13)$$

using the MK06 sample.

In a sequel paper, Hao et al. (2011) provide corrections to observed FUV or NUV luminosities based on TIR, warm dust or nonthermal radio radiation. Examples are:

$$\begin{aligned} L(\mathrm{FUV})_{\mathrm{corr}} &= L(\mathrm{FUV})_{\mathrm{obs}} + (0.46 \pm 0.12)L(\mathrm{TIR}) \\ L(\mathrm{NUV})_{\mathrm{corr}} &= L(\mathrm{NUV})_{\mathrm{obs}} + (0.27 \pm 0.02)L(\mathrm{TIR}) \end{aligned} \quad (14)$$

11. Wider applications

Remarks of caution have already been made that the above methods are developed with emphasis on studies of normal starforming galaxies as a function of redshift. However, the large amount of work undertaken in this area has helped in the studies of other kinds of galaxies and individual star forming regions in galaxies. The disagreement between different indicators, studied statistically, can help in understanding the general characteristics of a group. For example, Kaaret, Schmitt & Gorski (2011) found evidence for excess X-ray emission in BCD galaxies over what is expected from their SFR estimated using Hα, 24 μm, and FUV observations. The SFR estimates agree within a factor of two whereas the X-ray emission is an order of magnitude higher. On the other hand, Ramya, Kantharia & Prabhu (2011) found that the non-thermal radio emission is seven times lower in another sample of BCDs, compared to the expected value from SFR derived using Hα and TIR. Heesen et al. (2011) find a similar discrepancy, by a factor of three, in the post-starburst dwarf irregular galaxy IC 10, and suggest that a fraction of cosmic ray electrons have escaped the galaxy. Murphy et al. (2011) made a multiwavelength study of individual star forming regions in the nearby spiral NGC 6946 and conclude that the SFR estimated from the non-thermal radio radiation is an underestimate by a factor of 2-5, probably due to the diffusion of cosmic ray electrons beyond the star forming region. These results encourage further studies of statistical samples of individual star forming regions and different classes of dwarf galaxies.

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