Calibration of star formation rate tracers for short- and long-lived star formation episodes: far infrared and soft X-ray luminosities

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To derive the history of star formation in the Universe a set of calibrated star formation rate (SFR) tracers is required. Using evolutionary synthesis models, we have computed the predicted evolution of different estimators of the SFR assuming nearly-instantaneous (IB) and continuous star formation (EB) regimes, and the effect of interstellar extinction and metallicity.
A self-consistent calibration of a complete set of SFR tracers in the whole electromagnetic range has been obtained, focusing here on the far infrared and X-ray luminosities (FIR & Lx). We will show the web tool implemented to use the calibration developed and compare the predictions with previous calibrations of general use. Also, we will show how the estimators predictions can reproduce the FIR and Lx values of a sample of star-forming galaxies assuming usual ages of starburst regions, and using typical values for the parameters considered: extinction, and efficiency in the conversion from mechanical energy injected into the medium to X-rays emission.
Finally, we stress that in order to measure the intensity of star formation episodes we should distinguish between IB regimes, for which star formation strength ($M_\odot$) should be used, and EB regimes, for which the more common SFR ($M_\odot$ yr^{-1}) should be used.

THE CALIBRATION OF STAR FORMATION TRACERS

Emission over the whole electromagnetic range, from X-rays to radio energies, were calculated with **CMHK02** (Cerviño & Mas-Hesse 1994, Cerviño et al. 2002) and **Starburst99** (Leitherer et al. 1999) **evolutionary population synthesis models** in order to obtain a **self-consistent calibration of star formation tracers** to be applied on **starbursts** to characterize the star formation and quantify its intensity. The calibration is available as a **web tool** in http://www.laeff.cab.inta-csic.es/research/sfr/

The main features of these models are:

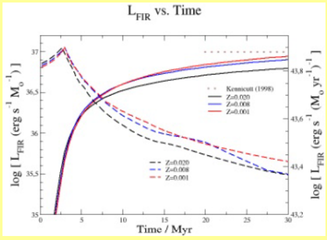
- **SFH:** extended bursts with constant star formation (**EB**), as well as instantaneous bursts (**IB**).
  - **EB models:** extended models. They assume constant star formation and are characterized by the value of the **star formation rate** (**SFR**) measured in **$M_\odot$ yr^{-1}**. Evolutionary states considered are Age=10, 30 and 250 Myr.
  - **IB models:** instantaneous models. No further star production after time=0 is assumed. Here, initial mass of the burst (**star formation strength, SFS**) is calculated in **$M_\odot$**. Ages=4, 5 and 6 Myr.
- **IMF:** nominally we assumed a Salpeter profile (ϕ(m)=A $m^{-2.35}$) with mass ranges considered being 2-120, 0.1-100, 1-100 $M_\odot$. Special care must be taken when comparing results from these models with other models which use different mass limits.
- **Magnitudes:** SFR/SFS can be calculated with the value of the number of ionizing photons, L(Lyα), L(Hα), continuum at 1500, 2000, 3500, 4400, 5500 and 22200 A, FIR for E(B-V)=0.1, 0.2, 0.3, 1, radio luminosity at 1.4 GHz or L_X(0.4-2.4 keV).
- **Metallicity:** a solar metallicity $Z_\odot$ is assumed as nominal, but different values were considered in order to study its effect on the estimators.

FIR LUMINOSITY

Concerning the **FIR luminosity**, a thermal equilibrium of dust is assumed, which implies all energy absorbed by dust being reemitted in the infrared range. The parameters present here are:

- **1-*f*:** fraction of Lyman continuum absorbed by dust, assuming 1-*f* = 0.3.
- **E(B-V):** extinction produced by the dust. L_{FIR} saturates very rapidly for E(B-V) > 0.5, so E(B-V) = 1 can be considered an upper value and we will assume it hereafter.

Completely obscured stars, whose radiation would be totally converted into FIR, are not considered.



Here, we show the L_{FIR} over time for both EB (scaled over SFR, right axis) and IB (scaled over the mass converted into stars, i.e. the total mass of the burst) models for various metallicity *Z* values. Once the most massive stars start to die, L_{FIR} decreases dramatically in the IB models. In the EB models these stars are replaced and therefore L_{FIR} approaches a steady state asymptotically. When lower *Z* values are considered, stellar lifetimes are higher and the accumulation of stars produces a higher FIR emission.

SOFT X-RAY LUMINOSITY

The **soft X-ray luminosity** is calculated in the 0.4-2.4 keV energy range. The sources which produce such emission are:

- Diffuse gas heated by the mechanical energy released into the ISM by stellar winds and supernovae.
- Supernova remnants.

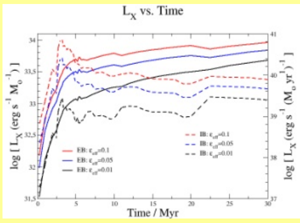
These contributions are modeled by a composite Raymond-Smith thermal plasma at k_BT=0.23, 0.76 and 1.29 keV for the latter and a fixed temperature k_BT=0.5 keV for the former (Cerviño et al 2002). There is actually one free parameter ε_{eff}: the fraction of mechanical energy released that ends up heating the gas up to X-rays temperatures.

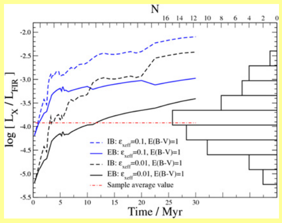
Some other X-ray radiation sources are ignored for this study:

- HMXBs: their contribution to the X-ray emission peaks at harder energies.
- LMXBs: they have not had time to form in the starburst, but contamination by an underlying population of the galaxy could be present.
- Stellar emission: intrinsic X-ray luminosity from the stars is negligible in our case.

L_{softX} AND L_{softX} TO L_{FIR} RATIO

In these graphs we present the evolution of the **X-ray luminosity** (the scaling is similar to the case of L_{FIR}) for different ε_{eff} values and the **ratio L_{softX}/L_{FIR}** of certain models which can reproduce the observational data (composed of three samples taken from the literature) represented by its total histogram.





L_{softX} in the IB models has a steeper increase at early ages whenever ε_{eff} value is assumed to be high and their L_{softX}/L_{FIR} value is about one order of magnitude larger than the ones from EB cases.

FROM WEB TOOL: http://www.laeff.cab.inta-csic.es/research/sfr/

Star formation history and age: EB (30 Myr)

Initial Mass Function: Salpeter 2-120

Magnitude observed LX(0.4-2.4 keV) (erg s-1)

Value of the magnitude observed = 3e+41

Color excess: E(B-V)=

Calculate

CALCULATE SFR

SFR(L_X(0.4-2.4 keV))= 6.00e+0 Mo yr^{-1}

The expected values for the different magnitudes are:

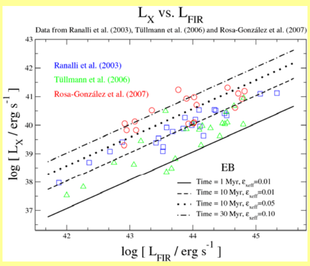
N_{Lyc} = 1.46e+54 s^{-1}	L_{5500} = 8.33e+39 erg s^{-1} Å^{-1}
L(Lyα) = 1.73e+43 erg s^{-1}	L_{22200} = 5.00e+38 erg s^{-1} Å^{-1}
L(Hα) = 1.99e+42 erg s^{-1}	L_{FIR}(E(B-V)=0.1) = 2.22e+44 erg s^{-1}
L_{1500} = 1.82e+41 erg s^{-1} Å^{-1}	L_{FIR}(E(B-V)=0.2) = 3.00e+44 erg s^{-1}
L_{2000} = 9.09e+40 erg s^{-1} Å^{-1}	L_{FIR}(E(B-V)=0.3) = 3.33e+44 erg s^{-1}
L_{3500} = 2.31e+40 erg s^{-1} Å^{-1}	L_{FIR}(E(B-V)=1) = 4.00e+44 erg s^{-1}
L_{4400} = 1.43e+40 erg s^{-1} Å^{-1}	L_{rad}(at 1.4 GHz) = 1.40e+29 erg s^{-1} Hz^{-1}

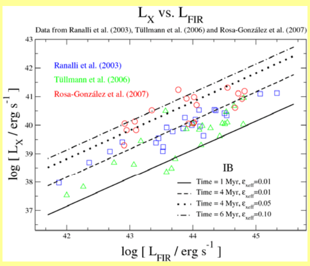
L_X TO L_{FIR} RATIO

Here we display the L_{softX} and L_{FIR} values from the data samples from Ranalli et al. (2003) (which we shall refer to as *Ran*), Tüllmann et al. (2006) (*Tul*) and Rosa-González et al. (2007) (*Rosag*) together with the predictions of our models for several values of ε_{eff}: 0.01, 0.05 and 0.1 at times 2, 10 and 30 Myr for EB and 2, 4 and 6 Myr for IB.

It can be seen in the plots that the observational data can be well reproduced by the synthesis models considering that the efficiency in conversion of mechanical energy is around 1-10%, a value which is consistent with previous studies. Moreover, our results show that the dispersion observed in the L_{softX} to L_{FIR} ratio can be explained as an **evolutionary effect**, i.e. using a standard value as standard SFR calibration can be **misleading** in some cases, and **the effect of starburst evolution should be taken into account**.

Therefore, we can infer from the results of our models that the sample from *Tul* is composed by younger bursts than *Ran* because early-time values tend to have a lower ratio L_{softX}/L_{FIR} -once a standard value for ε_{eff} is assumed-.





N.B. 1: In order to construct our sample, we took the values from *Tul* for those sources also present in the sample of *Ran*. Also, we removed three sources from the sample from *Rosag*, which may harbour an AGN, and one whose main X-ray component comes from LMXBs.
N.B. 2: L_{softX} are measured in the 0.5-2 keV energy range for the sources from *Ran*, in 0.3-2 keV for those from *Tul* and in 0.2-2 keV for those from *Rosag*. Hence, using $L_{0.4\text{-}2.4\,keV}$ needs a correction, which given the Raymond-Smith model assumed, is expected to be negligible: δ(log [L_{softX}/L_{FIR}]) < 0.05.

L_{softX} dominates as time increases and therefore low values of ε_{eff} are needed if we want to obtain values consistent with those of the samples during the complete periods shown.
The effect of time is more acute in IB models, as can be seen.

We can then extract the **calibration of SFR as a function of L_{softX}** purely from the L_{softX} values predicted by our models, which we split into two according to the evolutionary status of the burst: young burst (~10 Myr) and evolved burst (in the asymptotic phase). Respectively,

$$\mathbf{SFR(L_{softX})\ (M_\odot\ yr^{-1}) = 8\times10^{-41} L_{softX}\ (erg\ s^{-1})}$$
$$\mathbf{SFR(L_{softX})\ (M_\odot\ yr^{-1}) = 2\times10^{-41} L_{softX}\ (erg\ s^{-1})}$$

The expression for unevolved bursts is in accordance with the empirical relation proposed by Ranalli et al. (2003) within the uncertainties of the models, once the latter is corrected for the IR range and IMF mass limits used.
Also, in the case of IB bursts we can write a similar expression for Star Formation Strength, i.e. the total mass transformed into stars since the onset of the burst:

$$\mathbf{SFS(L_{softX})\ (M_\odot) = 2\times10^{-34} L_{softX}\ (erg\ s^{-1})}$$