Energy Balance in Dusty Environments: Truth and Myth

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For a system in equilibrium with energy sources absorbed by dust (e.g. stars in a dusty galaxy) the energy balance paradigm (EBP) can be stated as:

*The electromagnetic energy absorbed by the dust in the optical-UV must be equal to the energy which dust re-emits in the IR.*
Appeal and Caveats

The EBP appears linked to the energy conservation principle: 
*The total energy of a closed system cannot change* and therefore to the first law of thermodynamics. 
*For a closed thermodynamic system, the amount of energy added to the system by a heating process is equal to the sum of the amount of energy lost by the system due to work done by the system on its surroundings and of the change in the internal energy of the system.*

However these great ancestors should not blind you about the applicability of the principle.

The main caveats for the application of the EBP to dusty environments are:

1. The EBP is applicable only by summing energies emitted in all directions. These sums are difficult or impossible to estimate in case of anisotropic emission (e.g. AGN or asymmetric dust distribution).

2. In order to estimate the amount of energy absorbed by the dust in the optical-UV, a realistic assumption about the emitted spectrum must be made, which is not at all obvious and sometimes impossible (e.g. if the emitting sources are completely shielded or absorbed).

3. These problems are aggravated by the fact that dust not only absorbs radiation, but also scatters it, and the ratio depends on various factors, e.g. dust composition.

4. The effects of dust depend crucially on whether it is diffuse or clumpy.
Spectral energy distributions combining attenuated stellar population spectra with dust emission models:

(a) Quiescent star-forming galaxy
(b) Normal star-forming galaxy
(c) Starburst galaxy

Unattenuated stellar spectrum
Dust in stellar birth clouds
Dust in the ambient ISM
Total observed spectrum

CAVEATS:
Assumptions on SFH and IMF
Attenuation law
Average over viewing angles
For large sample, not for individual galaxies
NGC 4244, edge-on Sc galaxy, Holwerda et al. 2012

Optical image, SDSS

160 µm image, Herschel Space Obs.
NGC 4244 model with diffuse dust

all dust in a diffuse disk
$M_d = 0.5 \times 10^7 \, M_\odot$
$L_\star = 3.9 \times 10^9 \, L_\odot$

diffuse

all dust in MC clouds
$M_d = 1.4 \times 10^7 \, M_\odot$
$L_\star = 3.0 \times 10^9 \, L_\odot$

diffuse
NGC 4244 model with clumpy dust and embedded stars

all dust in a diffuse disk
$M_d = 0.5 \times 10^7 \, M_\odot$
$L_\star = 3.9 \times 10^9 \, L_\odot$

all dust in MC clouds
$M_d = 1.4 \times 10^7 \, M_\odot$
$L_\star = 3.0 \times 10^9 \, L_\odot + 3.7 \times 10^8 \, L_\odot$

diffuse
UV inside clouds
SFR indicators
(Kennicutt & Evans, ARAA 2012)

Log SFR (M$_{\odot}$/year) = log $L_x$ – log $C_x$

<table>
<thead>
<tr>
<th>Band</th>
<th>Age range (Myr)$^a$</th>
<th>$L_x$ units</th>
<th>log $C_x$$^b$</th>
<th>$\dot{M}<em>*$/$\dot{M}</em>*$ (K98)$^c$</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUV</td>
<td>0-10-100</td>
<td>ergs s$^{-1}$ ($\nu L_v$)</td>
<td>43.35</td>
<td>0.63</td>
<td>Hao et al. (2011), Murphy et al. (2011)</td>
</tr>
<tr>
<td>NUV</td>
<td>0-10-200</td>
<td>ergs s$^{-1}$ ($\nu L_v$)</td>
<td>43.17</td>
<td>0.64</td>
<td>Hao et al. (2011), Murphy et al. (2011)</td>
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<tr>
<td>Hα</td>
<td>0-3-10</td>
<td>ergs s$^{-1}$</td>
<td>41.27</td>
<td>0.68</td>
<td>Hao et al. (2011), Murphy et al. (2011)</td>
</tr>
<tr>
<td>TIR</td>
<td>0-5-100$^d$</td>
<td>ergs s$^{-1}$ (3–1100 μm)</td>
<td>43.41</td>
<td>0.86</td>
<td>Hao et al. (2011), Murphy et al. (2011)</td>
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<tr>
<td>24 μm</td>
<td>0-5-100$^d$</td>
<td>ergs s$^{-1}$ ($\nu L_v$)</td>
<td>42.69</td>
<td></td>
<td>Rieke et al. (2009)</td>
</tr>
<tr>
<td>70 μm</td>
<td>0-5-100$^d$</td>
<td>ergs s$^{-1}$ ($\nu L_v$)</td>
<td>43.23</td>
<td></td>
<td>Calzetti et al. (2010b)</td>
</tr>
<tr>
<td>1.4 GHz</td>
<td>0-100</td>
<td>ergs s$^{-1}$ Hz$^{-1}$</td>
<td>28.20</td>
<td></td>
<td>Murphy et al. (2011)</td>
</tr>
<tr>
<td>2–10 keV</td>
<td>0-100</td>
<td>ergs s$^{-1}$</td>
<td>39.77</td>
<td>0.86</td>
<td>Ranalli et al. (2003)</td>
</tr>
</tbody>
</table>

$L_{\text{FUV(corr)}} = L_{\text{FUV(observed)}} + \eta L_{\text{TIR}}$

This is very different from:
SFR$_{\text{Tot}} = $ SFR$_{\text{FUV}}$ + SFR$_{\text{TIR}}$