Research Note

Infrared bolometric corrections for AGB stars with circumstellar shells

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Summary. The two-colour diagram based on the IRAS 12, 25, and 60 μm flux densities has proven to be a very useful tool for studying the evolution of stars with circumstellar shells that are at the top of the Asymptotic Giant Branch (Van der Veen and Habing, 1988; hereafter Paper I). For a proper analysis of the data it is essential to know the total flux, and therefore it is useful to define an infrared bolometric correction (hereafter IR-bolometric correction) in terms of the IRAS photometry.

In this paper we derive such IR-bolometric correction for AGB stars associated with different regions in the IRAS two-colour diagram. These corrections can then be used in statistical studies that make use of the diagram.

Key words: stars: bolometric correction – stars: long-period variables – stars: OH/IR

1. Introduction

In Van der Veen and Habing (1988) (hereafter Paper I), the distribution of evolved stars in the Infrared Astronomical Satellite (IRAS) two-colour diagram of the 12, 25, and 60 μm flux densities has been discussed. At the same time that stars, with increasingly thicker circumstellar shells, “disappear” from the Asymptotic Giant Branch (AGB) in the (optically determined) Hertzsprung-Russell diagram, the stars move away from the Rayleigh-Jeans point in the IRAS two-colour diagram and enter a large area. The location of stars in the IRAS two-colour diagram gives information about their evolutionary status (e.g. Mira variable, OH/IR star, planetary nebula) and about their composition (oxygen-rich or carbon-rich circumstellar shells).

We may hope that in the future the IRAS two-colour diagram provides a tool as powerful to understand the AGB evolution as the HR-diagram was for understanding the earlier phases in stellar evolution. Therefore it is useful to define an IR-bolometric correction for these stars analogous to the bolometric correction used in the HR-diagram.

2. Definition of the “IR-bolometric correction”

First we choose a wavelength at which the IR-bolometric correction will be defined. For stars in the HR-diagram a wavelength corresponding to the maximum sensitivity of the human eye is used ($\lambda = 0.55 \mu m$). For the IRAS two-colour diagram we propose the wavelength at which IRAS was most sensitive: $\lambda = 12 \mu m$. Because the IRAS flux density is normally given in flux density units (Jy) instead of magnitudes, we define an IR-bolometric correction in terms of fluxes

$$ BC_{12} = \int_0^\infty F_{\nu} \frac{d\nu}{(\nu F_{\nu})}_{12 \mu m}. $$

Second we have to find a parameter that characterizes a star sufficiently to assume that there is a unique IR-bolometric correction; this parameter will have to be a measure for the temperature of the source. For the bolometric correction defined at visual wavelengths the $B-V$ colour is used. We propose to use the [12]–[25] colour defined as

$$ C_{21} = [12]-[25] = 2.5 \log \left( \frac{F_{25}}{F_{12}} \right). $$

The definition of the IR-bolometric correction given by Eqs. (1) and (2) is similar to the one proposed by Herman et al. (1986). In Fig. 1 the IR-bolometric correction is plotted as a function of [12]–[25] for the simplified case that stars radiate as black bodies with temperatures between 100 and 5,000 K. The IR-bolometric correction is a very steep function of [12]–[25] for [12]–[25] < −0.8 ($T_{\text{BB}} > 500$ K). It reaches a minimum of 2.0 for [12]–[25] = 0.0 ($T_{\text{BB}} = 300$ K) and then increases again towards redder colours.

3. The data

We have searched the literature for photometric data on AGB stars with circumstellar shells. A distinction is made between stars with oxygen-rich circumstellar shells and stars with carbon-rich circumstellar shells. As discussed in Paper I the position in the IRAS two-colour diagram does not uniquely determine the chemical composition (O- or C-rich). In a statistical sense, however, the regions II, IIIa/b, IV, and V contain mostly oxygen-rich stars and region VII contains mostly carbon-rich stars. To ensure that the selected sources are representative for the different

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regions in the IRAS two-colour diagram we have checked whether the sources taken from the regions II, IIIa, IIIb, IV, and V really have oxygen-rich shells and whether the sources taken from region VII really have carbon-rich shells (see Fig. 2). Their photometry between 12 and 60 μm is obtained from the IRAS Point Source Catalog (IRAS PSC, 1985), where we have only used sources with good quality \( Q = 3 \) flux densities at 12, 25, and 60 μm. We did not use the 100 μm flux density, because for most sources this flux density is unreliable.

In the regions II, IIIa, and VII of Fig. 2 (optically thick circumstellar shells) most of the chosen bright infrared sources have also been detected in the CO \( (J = 1 - 0) \) or CO \( (J = 2 - 1) \) line (Knapp et al., 1982; Knapp and Morris, 1985; Zuckerman and Dyck 1986a, b; Zuckerman et al., 1986; Wannier and Sahai, 1986), which is an additional proof that these stars are indeed surrounded by an expanding circumstellar shell. Further, we have only used sources with simultaneous infrared photometry that cover the wavelength range between 1 and 13 μm (Gezari et al., 1987). For most of the sources in the regions II and IIIa we have found the

9.7 μm feature in emission (from the photometry around 10 μm and the IRAS LRS spectra), confirming that the circumstellar shells are oxygen-rich. For most of the sources in region VII the 11.3 μm feature appears (always in emission), confirming that these sources are indeed surrounded by carbon-rich circumstellar shells. In total we have used 46 oxygen-rich stars (regions II and IIIa) and 30 carbon-rich stars (region VII).

In the regions IIIb and IV of Fig. 2 (optically thick circumstellar shells) most of the chosen bright infrared sources have also been detected in the OH (1612 MHz) line (te Lintel Hekkert et al., 1989), which is an additional proof that these stars are surrounded by an expanding, oxygen-rich, circumstellar shell. Simultaneous photometric data between 1 and 12 μm are taken from various sources (Gezari et al., 1987; Herman et al., 1984; Van der Veen and Habing, 1989; Van der Veen et al., 1989). From the photometry around 10 μm we have found that for most of these sources the 9.7 μm feature is in absorption, again confirming that they are surrounded by optically thick, oxygen-rich, circumstellar shells.

For stars in transition to the planetary nebula stage, and for some rather obscured planetary nebulae (regions IV and V) we have used simultaneous photometric data from Van der Veen et al. (1989). In total we have used 44, 18, and 8 stars for the regions IIIb, IV, and V respectively.

The total sample was chosen so that the sources are about equally distributed in the regions II, IIIa, IIIb, IV, V, and VII (Fig. 2); oxygen-rich stars are indicated by black dots, carbon-rich stars are indicated by open circles. We recall that the stars chosen from the regions II, IIIa, IIIb, IV and V were checked individually to be oxygen-rich; the stars chosen from region VII were checked individually to be carbon-rich.

4. Calculations and results

From the available photometry we have calculated the flux density, \( F_\nu \), at different wavelengths between 1 and 60 μm. For calibration we used the calibration constants for a 0.0 mag star as given by Wamsteker (1981) and Le Bertre (1984). These calibration constants are only valid for the ESO infrared system; for data obtained with other infrared systems the calibration con-
stants are slightly different. The differences, however, are small compared with other errors in the determination of the total flux (see below). Because most sources are variable and the IRAS measurements were done at an epoch different from that of the ground-based observations, we split the wavelength range in 2 parts: one for $\lambda < 12\,\mu m$ and one for $\lambda > 12\,\mu m$; the ground-based observations between 1 and 12 $\mu m$ are simultaneous. Next we calculated the IR-bolometric correction separately for $\lambda < 12\,\mu m$ and $\lambda > 12\,\mu m$.

$$BC_{12}(\lambda < 12\,\mu m) = \left\{ \int_0^{1\,\mu m} B_{\lambda}(T_\star) \, d\lambda + \int_{1\,\mu m}^{12\,\mu m} F_{\lambda}(T_\star) \, d\lambda \right\} (\lambda F_{12})_{12\,\mu m}, \hspace{1cm} (3a)$$

$$BC_{12}(\lambda > 12\,\mu m) = \left\{ \int_{60\,\mu m}^{12\,\mu m} F_{\lambda}(T_\star) \, d\lambda + \int_{60\,\mu m}^{\infty} B_{\lambda}(T_\star) \, d\lambda \right\} (\lambda F_{12})_{12\,\mu m}, \hspace{1cm} (3b)$$

where $F_{12}$ is the observed ground-based flux density, and where $F_{2\lambda}$ is the observed IRAS flux density.

The first integral in Eq. (3b) and the second integral in Eq. (3a) were calculated by connecting all observed flux densities by a straight line and by integrating under the curve. This is accurate to within 10–20%. The first integral in Eq. (3a) was only calculated when the 1–2 $\mu m$ photometry corresponds to a black body colour temperature, $T_\star$, larger than about 1,000 K. If $T_\star < 1,000$ K, the first integral contributes less than 1% to the total IR-bolometric correction; for $T_\star = 2,000$ K, however, this contribution is already 20%. The second integral in Eq. (3b) was only calculated when the $[25]–[60]$ colour corresponds with a black body temperature, $T_\star$, smaller than 400 K; for $T_\star > 400$ K this integral contributes less than 1% to the total IR-bolometric correction.

The error in the $[12]–[25]$ colour is about 0.15 mag, assuming an error in the individual flux densities of 10%. The error in the IR-bolometric correction is fully caused by the uncertainties in the calculation of the total flux. The effect of the variability of the sources is for a large part eliminated by dividing the total fluxes by the energy at 12 $\mu m$ measured at identical times (Eqs. 3a and 3b respectively). A small uncertainty remains, as a consequence of the change in shape of the whole spectrum over one pulsation period. Enke et al. (1983), however, have shown that this effect is small.

The error in the calculation of the second integral in Eq. (3a) and the first integral in Eq. (3b) is about 10% as mentioned before. The error in the calculation of the first integral in Eq. (3a) and the second integral in Eq. (3b) depends on the accuracy in the determination of the colour temperature $T_\star$. Roughly we estimate that the error in both integrals is about 30%. Thus, depending on the shape of the spectrum, the expected uncertainty in the determination of the IR-bolometric correction is between 10 and 30%.

The results of the calculations are shown in Fig. 3a and b for oxygen-rich stars and carbon-rich stars respectively. The spread in the points is mainly caused by the uncertainties in calculating the IR-bolometric correction. This uncertainty is largest for $[12]–[25] < 0$, because these stars have still an optical counterpart, and the first integral in Eq. (3c) has to be calculated.

To find a suitable function to fit the observed points we go back to Fig. 1. For a black body of different temperatures, $T$, the IR-bolometric correction is proportional to $T^4$ (const./$T$) – 1), where $T \sim \exp (a \, C_{21})$ ($a < 0$) for $C_{21} = [12]–[25] = -1.1$. If we substitute $T$ in the equation for BC we find that for $C_{21} < -0.2$ (high temperatures), $BC \sim \exp (a_1 \, C_{21})$ with $a_1 < 0$, and that for $C_{21} > 0.2$ (low temperatures), $BC \sim \exp (a_2 \, C_{21})$ with $a_2 = 0$. From this we conclude that a suitable fit is a function of the form $BC = b_0 + b_1 \exp (-b_2 \, C_{21}) + b_3 \exp (b_4 \, C_{21})$.

**Fig. 3a.** The IR-bolometric correction as a function of $[12]–[25]$ for AGB stars with oxygen-rich circumstellar shells situated in the regions II (asterisks), IIIa (open circles), IIIb (black dots), IV (open triangles), and V (crosses) of Fig. 2. The full line is a best fit given by Eq. (4a) see text.

**Fig. 3b.** The IR-bolometric correction as a function of $[12]–[25]$ for AGB stars with carbon-rich circumstellar shells situated in the region VII. The full line is a best fit given by Eq. (4b) see text.

The best values for the constants in this relation for oxygen-rich stars (regions II, IIIa, IIIb, IV, and V) and for carbon-rich stars (region VII) are given by

**oxyng-rich stars:**

$$BC_{12} = 0.7 + 2.9 \exp (-3.0 \, C_{21}) + 0.9 \exp (0.7 \, C_{21}),$$

**carbon-rich stars:**

$$BC_{12} = 3.5 + 8 \times 10^{-4} \exp (-7.6 \, C_{21}).$$

The mean deviation from Eq. (4a) of individual points is 30% for the whole sample and respectively 40%, 50%, 15%, 15%, and 10% for the sources in the regions II, IIIa, IIIb, IV, and V of Fig. 2, this value is 40% for the sources in region VII of Fig. 2. The deviations are of the same order as the uncertainties in the IR-bolometric correction, which we expect to decrease for sources with redder $[12]–[25]$ colours.

If we want to do a (statistical) study of a sample of IRAS sources that is selected from one of the regions II, IIIa, IIIb, IV, V...
Table 1. Mean values of the IR-bolometric correction for the different regions in the IRAS two-colour diagram

<table>
<thead>
<tr>
<th>Region</th>
<th>$BC_{\text{min}}$</th>
<th>$BC_{\text{max}}$</th>
<th>$BC^a$</th>
<th>$BC^b$</th>
<th>$BC^c$</th>
<th>$BC^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>$&gt;100$</td>
</tr>
<tr>
<td>II</td>
<td>33</td>
<td>107</td>
<td>59</td>
<td>53</td>
<td>63</td>
<td>60</td>
</tr>
<tr>
<td>IIIa</td>
<td>3.3</td>
<td>33</td>
<td>17</td>
<td>10</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>IIIb</td>
<td>2.5</td>
<td>3.1</td>
<td>3.0</td>
<td>2.9</td>
<td>2.7</td>
<td>3</td>
</tr>
<tr>
<td>IV</td>
<td>2.5</td>
<td>3.1</td>
<td>3.1</td>
<td>3.0</td>
<td>2.7</td>
<td>3</td>
</tr>
<tr>
<td>V</td>
<td>3.1</td>
<td>8.0</td>
<td>5.3</td>
<td>4.9</td>
<td>6.7</td>
<td>$&gt;5$</td>
</tr>
<tr>
<td>VIa</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>$&gt;100$</td>
</tr>
<tr>
<td>VIb</td>
<td>--</td>
<td>--</td>
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<td>--</td>
<td>--</td>
<td>3?</td>
</tr>
<tr>
<td>VIIe</td>
<td>3.5</td>
<td>37</td>
<td>13</td>
<td>8.3</td>
<td>7.9</td>
<td>8</td>
</tr>
<tr>
<td>VIIc</td>
<td>5.1</td>
<td>37</td>
<td>19</td>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>VIIg</td>
<td>3.5</td>
<td>5.1</td>
<td>5.7</td>
<td>4.8</td>
<td>3.9</td>
<td>4</td>
</tr>
<tr>
<td>VIII</td>
<td>--</td>
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<td>--</td>
<td>--</td>
<td>--</td>
<td>3?</td>
</tr>
</tbody>
</table>

*Arithmetic mean; $^b$ geometric mean; $^c$ mean calculated from equations (4a) and (4b); $^d$ value to use for statistical purpose; $^e$ whole colour range; $^f$ [12]–[25]< −1.0; $^g$ [12]–[25]> −1.0

or VII, it is convenient to have a typical value for the IR-bolometric correction of those sources. To find a mean IR-bolometric correction for the different regions we proceeded in different ways. First we have calculated the arithmetic mean of all individual points, second we calculated the geometric mean of all points, and third we have calculated a mean from the Eqs. (4a) and (4b). The results are listed in Table 1.

We have also indicated the minimum and maximum IR-bolometric correction according to equations (4a) and (4b). In the last column we propose some round values for BC to be used in statistical studies of the IRAS two-colour diagram; they are a best compromise between the different averages for the different regions. The value for the IR-bolometric correction for sources in region V is a lower limit. The IR-bolometric correction has only been determined for some, still largely obscured, planetary nebulae. When the central source starts to shine through the dust shell the IR-bolometric correction can be significantly larger.

5. Conclusions

The IRAS two-colour diagram is a useful tool to study the evolution of stars on and beyond the AGB (Paper I). Therefore it is useful to define an IR-bolometric correction for these stars in terms of the IRAS photometry. We have chosen $\lambda = 12\,\mu\text{m}$ as the wavelength where the IR-bolometric correction is defined, and the [12]–[25] colour as the temperature parameter for the IR-bolometric correction.

We have calculated the IR-bolometric corrections for IRAS sources situated in different regions of the IRAS two-colour diagram described in Paper I, but only for those regions that are populated by AGB stars with (both oxygen- and carbon-rich) circumstellar shells, and for which an IR-bolometric correction, defined as a function of the IRAS [12]–[25] colour, is meaningful.

We did not extend our discussion to sources in the regions I, VIa, VIb and VIII. Sources in region I have hardly any far infrared excess and the IR-bolometric correction defined at visual wavelengths can be used. Many optically identified carbon stars are situated in region VIa (see Paper I). These carbon stars have an excess at 60 $\mu$m, but the energy radiated at this wavelength is small in comparison with the total energy. Therefore the IR-bolometric correction defined at visual wavelengths can still be used for these stars.

Sources in region VIb and VIII are not discussed either, because there is a lack of photometric data for these sources. The majority have no or very faint optical counterparts, similar to the sources in the regions IIIb and IV, suggesting that the IR-bolometric correction is also similar to the ones we have found for the regions IIIb and IV.

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