THE DEVELOPMENT OF STELLAR PHOTOMETRIC STANDARDS FOR ISO

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ABSTRACT

The ISO ground-based preparatory programme working group (ISO-GBPPwg) was set the goal in 1990 to characterise accurately in the infrared some 400 stars covering the whole sky. Telescopes in Chile, Hawaii and the Canary Islands were used to obtain J, H, K, and L photometry for all of these stars and, for the brightest ones, spectroscopy and/or N and Q bolometry. The stars were chosen single and non-variable, with spectral type in the range K9 to A0 and luminosity class III to V. The stellar effective temperatures (T_e) were determined using the Infrared Flux Method and the $V-K$ versus T_e relationship. The results from both methods were combined with the surface gravity and metallicity to give the spectral energy distributions up to about 50 μm, from the Kurucz stellar model atmosphere grids. Tests were then made to confirm the accuracy of the spectral energy distributions over the required wavelength range.

Key words: techniques:photometric, stars: fundamental parameters, infrared:stars, standards

1. INTRODUCTION

Scientific observations can only be as accurate as the calibrations upon which they are based. However, the nature of ISO (Kessler et al. 1996) meant that there were significant problems in compiling the necessary data base:

- ISO was designed to work at wavelength ranges that in general are not visible from the ground
- the limited lifetime of ISO, coupled with the high number of possible configurations, meant that there would not be time to use the satellite itself to set up its own calibration data base
- the sources had to cover a large dynamic range, as only the very brightest sources would make useful calibrators at wavelengths longer than 20 μm, but far fainter sources would be required for ISO-CAM
- ISO could only see a very restricted area of sky at any one time, so sources were required over the whole sky.

This work was, in the end, one of two programmes which delivered stellar spectral energy distributions (SEDs). The other one was based on the Cohen templates (Cohen 1996 and these proceedings). Furthermore there were other calibrators used at the longer wavelengths. This presented the additional complication of ensuring that there would be no systematic differences between the various calibration data sets.

1.1. HISTORY OF THE ISO-GBPPWG

The ISO ground-based preparatory programme working group (ISO-GBPPwg) was created in 1989 and chaired by H. J. Habing. The goal of the working group was to define the ground-based preparatory work that was needed in order to optimise ISO observations. Representatives of each of the four ISO instruments participated in the first meetings. Several ground-based observational programmes were identified. Programmes that were specific to a particular ISO science programme and/or ISO instrument became the responsibility of the relevant Co-I's. The accurate flux calibration in the near- to far-infrared, however, clearly concerned most of the ISO instruments and science programmes. The mid-infrared calibration, in particular, was poorly defined at that time. In mid-1990 the ISO-GBPPwg set up the goal of establishing a set of Infrared Standards for ISO. Several experts in infrared calibration, infrared stellar spectroscopy, as well as potential observers, joined the working group at this stage (Jourdain de Muizon and Habing 1992). The project was endorsed by the ISO Science Team.

An ESO Key-programme proposal was submitted running over several observing periods; about 60 nights were granted. In parallel similar observations were carried out in the Northern Hemisphere (Canary Islands and Hawaii). In total about 400 stars were observed in several near- and mid-infrared bands. The ISO-GBPPwg held several workshops between 1991 and 1994 in order to select the stars, prepare the observations and discuss the results with theoreticians. In mid-1995 the ISO-GBPPwg delivered the photometric data and the requested SEDs to the ISO calibration working group. Further deliveries were then made during the course of the mission.

1.2. REQUIREMENTS

The ISO-GBPPwg was asked to provide SEDs which would form the basis for the ISO calibration between 2.4 and 50 μm. The top level requirements were:

- flux accuracy of 5% at 10 μm and 10% at 50 μm
- magnitude range $-3 < m_K < 9$
- about 400 sources covering the whole sky

- spectral types A to M
- the sources must be good calibrators. i.e. single, non variable etc.

2. THE METHOD

The method that was pursued is outlined in Figure 1. The first step is to determine the stellar effective temperatures (T_e) using the infrared flux method (IRFM, Blackwell et al. 1998) or the $V - K$ vs T_e relationship (Di Benedetto 1998). To achieve this, near-infrared and visible photometry of the sources was required. Where possible metallicity and surface gravity measurements from the literature were also used. However, often these were not available and in such cases it was assumed that the metallicity was solar and the surface gravity was derived from the spectral type and luminosity class. In any case the effect of metallicity and surface gravity on the SEDs in the infrared is small.

The effective temperature, metallicty and surface gravity are then introduced into stellar models to obtain the shape of the SED. The high numbers of stars involved made it impractical to consider running specific models for each star. Rather it was decided to interpolate within the Kurucz (1993) model grids. These cover a wide range of effective temperatures (T_e), metallicities and surface gravities and have a sufficiently high spectral resolution in the near IR that the majority of the major stellar features (e.g. CO) are clearly visible. This grid is derived using the ATLAS 9 code (Kurucz 1991). One disadvantage of this grid, however, is that SiO bands are not present and these form a major feature near 8 μm. Hence great care must be taken when using the results for the cool stars, near the SiO bands, as will be discussed later.

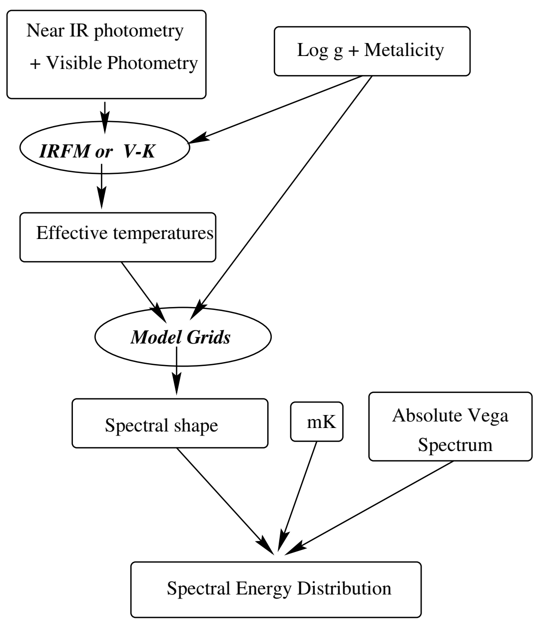

Figure 1. The flow diagram which shows how the data were used to produce the spectral energy distributions.

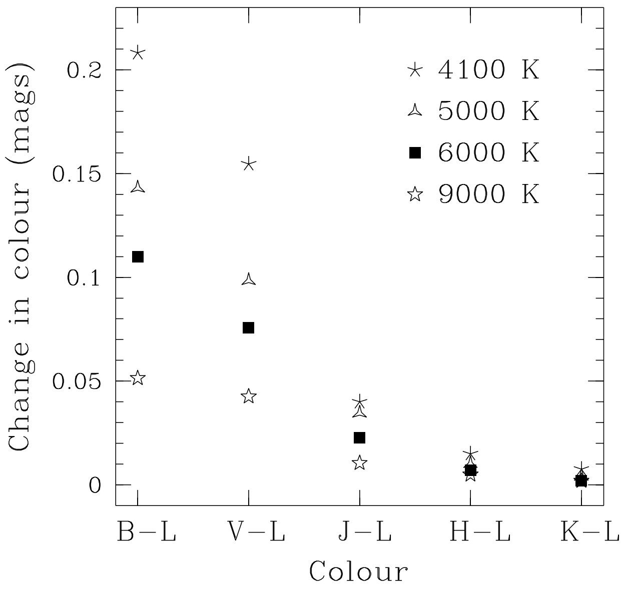

Figure 2. The change in colour for a 2% change in T_e.

The spectral shape of the stars is then normalised to the K photometry to produce the final SED. A magnitude is simply the ratio of the in-band flux from the star to that of the zero point, and we have adopted Vega as being zero magnitude at all wavelengths. Tokunaga (1984) shows that there is no evidence of an IR excess in Vega in the $N - Q$ colour. However, the model SEDs were required to extend beyond 30 μm, where the IR excess of Vega (Aumann et al. 1984) is significant. Hence the true Vega flux density could not be used as the zero point for the longest wavelengths.

There remains, however, some controversy over what is the absolute Vega flux density in the infrared, a discussion of which is provided in Mégessier (1995) or Cohen et al. (1992). However, the black body approximation to Vega suggested by Mégessier is unacceptable in this case as it is not clear that the approximation is applicable at 25 μm. Furthermore the models are based on the Kurucz grids, therefore it is preferable to use a Vega model also derived from the same source.

The photospheric Vega model that we have chosen to adopt is that presented in Cohen et al. (1992), which is a customised Kurucz model that incorporates the metal poor character of Vega. This has a nominal error of 1.45% and in general is within a few percent of other determinations in the near IR. The absolute calibration of the Cohen templates is also based upon the same Vega model and hence the basis for the absolute calibration of all the stellar SEDs used for ISO is the same.

It was decided to use only the K-magnitude to normalise the SEDs, rather than all of the photometry, because the predictions were for wavelengths longer than 2.4 μm. Figure 2 shows the change in colour between $BVJHK$ and L when T_e changes by 2% for a number of temperatures. The L filter is within the ISO wavelength range and, as can be seen, the closer the wavelength of the other filter is to the L filter the smaller is the change in colour. Even for the coolest stars $K - L$ changes by under 0.01 magnitude whereas it is over 0.2 magnitude for $B - L$. This plot suggests that, were it necessary to calibrate infrared measurements from solely visible measurements, then only hotter stars should be used.

3. THE OBSERVATIONS

There are a large number of near-infrared photometric systems, but in order to provide a homogeneous data set over the whole sky we could not simply combine the various systems. Moreover more than one observatory would have to be used to give coverage of both the northern and southern hemispheres. Therefore the requirements that we set were:

- the systems used must have measured pass-bands for each filter (including optics and detector) at the operating temperature. This is then combined with the atmospheric transmission to give the total transmission. All calculations are then based on integrating the SEDs across the band passes
- where possible narrow-band filters should be used. These can be aimed at continuum regions of the stellar spectrum and the best parts of the atmospheric windows, which makes the results less sensitive to changes in atmospheric conditions
- the systems must have clearly defined zero points
- a number of stars must be measured in all of the systems used.

In the end four filter systems were settled upon, two in the northern hemisphere and two in the southern hemisphere:

- the Selby narrow-band system. This has narrow band Jn, Kn and Ln and was built to obtain photometry for use with the IRFM. In Selby et al. (1988), photometry on some 160 sources were published. For the ISO calibration this was extended by some 60 sources using the 1.5m TCS (Tenerife) and the 4.2m WHT (La Palma)
- the standard photometer on the 1.5m TCS (Tenerife). This has broad band JHK and L and, being broad-band, it goes deeper than the Selby narrow-band system. The ISO calibration work was built upon the existing TCS standards, however a significant amount of work was done to tie the zero points to Vega
- ESO broad-band. This gave broad-band $JHKL$ and M and built upon the work of Bouchet et al. (1991). The observations were made using principally the 1m and 2.2m telescopes at La Silla (van der Bliek et al. 1996)
- ESO CVF. This was a system especially set up for the ISO calibration programme and used the CVF segment to give narrow pass bands at continuum regions between 1.5 and 3.7 μm plus Brackett gamma and CO (van der Bliek et al. 1996).

In addition to the near-IR photometry, some bolometry at ESO and on the IRTF (Hawaii) was obtained in the N and Q bands, as well as spectra of some sources using the NTT (La Silla) and UKIRT (Hawaii).

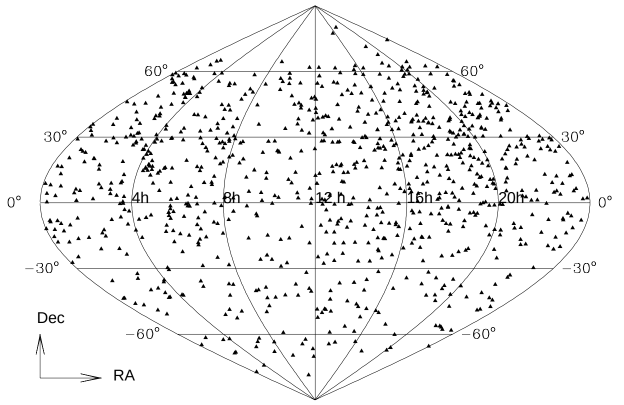

Figure 3. The distribution of the sources on the sky.

After obtaining the various data sets, checks were made to ensure the uniformity of the results, in particular the consistency of the zero points, and to correct any non-linearity.
In total there were over 500 sources from which the calibration stars could be chosen. Their distribution upon the sky is shown in Figure 3.

4. DELIVERED PRODUCTS

The first products delivered to the ISO instrument teams were the photometric catalogues plus supplementary data on the sources, from which the selection of the sources to be used in the mission could be made. SEDs of the selected sources were then sent when they were requested, the first deliveries being made in the month before launch and continuing during the mission.

The SED files contained a header which listed the products used to build the SED, then the wavelength, flux in $\mathrm{W\,m^{-2}\,\mu m^{-1}}$, flux in Jy and flux error. As the wavelength spacing beyond 10 μ becomes very course, an interpolation in $\lambda^4 f(\lambda)$ was used to increase the number of points between 10 and 160 μm. The error was determined by combining:

- the errors in the measurements
- models extracted at various T_e, metallicities and Log g around the value used. This allowed error from these parameters to be assessed
- the error in the absolute spectra (for many wavelength ranges this was the major error source)

Two example SEDs are shown in Figure 4. The upper plot shows the extracted SED for Vega (dashed line) with the errors (dotted lines) after following the above procedures. Also plotted is the photospheric model of Vega used as the basis for the absolute calibration. As can be seen the difference between the two is under 0.5%. The lower plot shows the extracted spectrum and quoted errors (typically 3% to 4%) for HR 6705, which turned out to be one of the principal calibrators used throughout the mission. Also shown is the Cohen template for

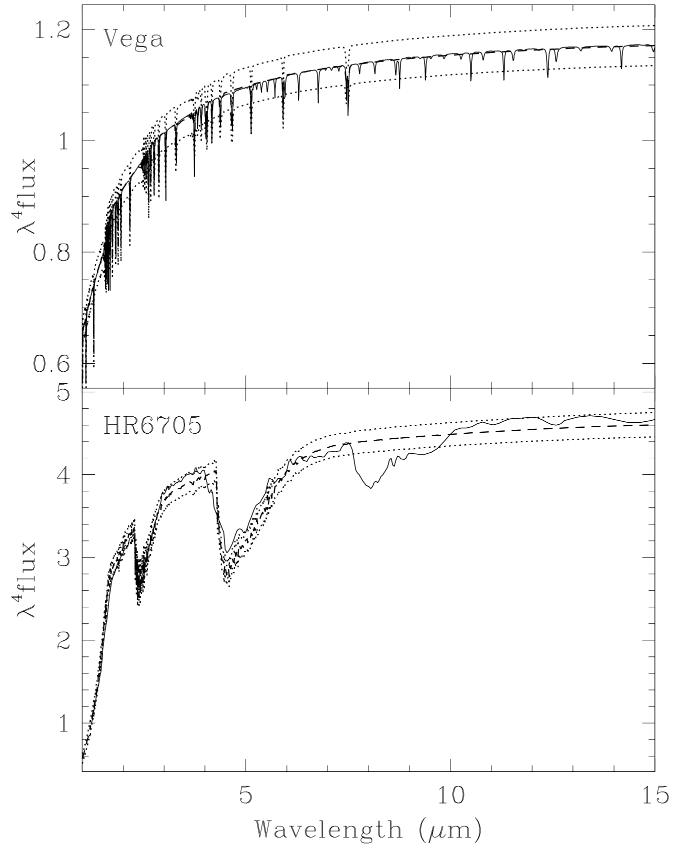

Figure 4. Predicted SED's for Vega and HR 6705 (dashed lines) and the quoted error for the SEDs. The absolute Vega model is shown on the Vega plot, and the Cohen template on the HR 6705 plot.

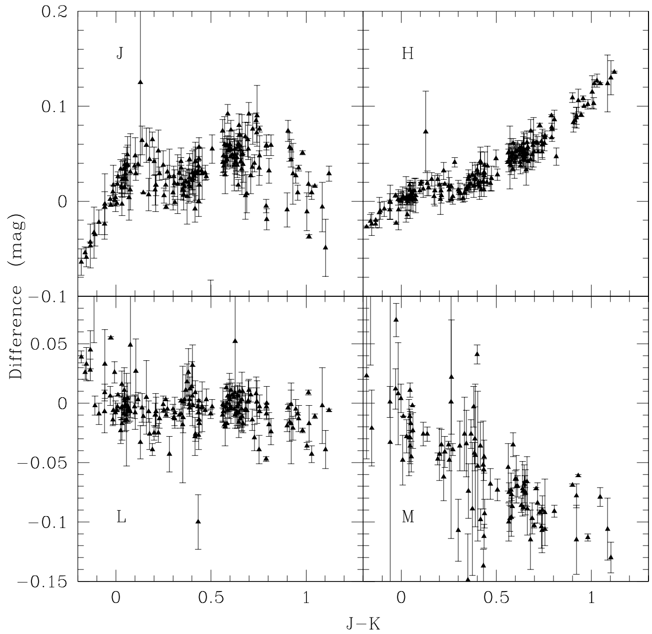

Figure 5. The difference between the measured and predicted magnitudes at JHL and M against $J-K$. The error bars from the measurements are also plotted.

the same star. As can be seen the agreement is good apart from a few areas. The SiO fundamental at 8 μm is not in the model. Neither is the first overtone at about 4 μm, and in these two regions the model is significantly above the template. The CO fundamental at 5 μm is, however, too strong in the model. Care should be taken when using the models for the cool stars in these regions. However, apart from these regions, both the templates and the models are in very good agreement.

5. VERIFYING THE PREDICTIONS

In order to verify that the SEDs met the required accuracy levels, a series of tests were performed which compared the predicted and measured magnitudes in various filters.

5.1. Near-Infrared Magnitudes

Figure 5 shows the difference between the measured and predicted magnitudes at J H L and M against $J-K$. For both of the shorter wavelengths the predictions are fairly poor. For H, in particular, the model flux predictions are over 10% too high for the coolest stars. The 1.5 μm region is one of the most difficult to model as the opacity is at a minimum, and so the line-of-sight travels deeper into the star. These plots give further reasons why, when predicting for the ISO wavelength range, it is better to normalise to the K-filter.

Apart from a few poorer points the L predictions are accurate and show little drift with temperature. However, the M-filters do show a significant trend, mostly caused by the over prediction of the strength of the CO lines, as noted previously.

5.2. *IRAS*

Figures 6 and 7 show the difference between the measured *IRAS* magnitudes and those predicted from the SEDs at 12 and 60 μm. The *IRAS* point source catalogue was converted into magnitudes using the conversion factors given in Cohen et al. (1992). In the 12 μm plot most of the stars lie very close to zero. The standard deviation for 490 sources is 0.07 magnitudes, which is dominated by the error in the *IRAS* measurement. However, the average displacement is only 0.004 magnitudes, which means that the zero points are in very good agreement with those determined in Cohen et al. (1992). The predictions appear to be equally accurate for giants and dwarfs. Also, there is no significant trend with temperature. The only possible exception being an effect at the 1% level in the stars cooler than 4500 K due to the model not including the SiO bands which do affect the 12 μm filter. There are a few stars which are significantly brighter in *IRAS* than predicted, these are almost certainly stars with infrared excesses and therefore they should not be used as standards.

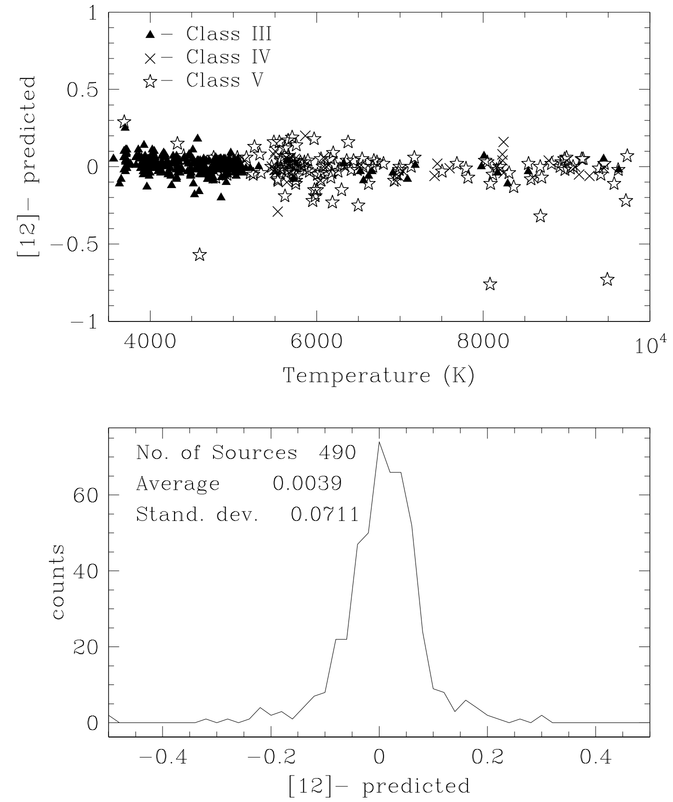

Figure 6. The difference between the measured and predicted magnitudes for $IRAS$ at 12 μm. The upper plot shows the difference with temperature and the lower shows the histogram of the distribution.

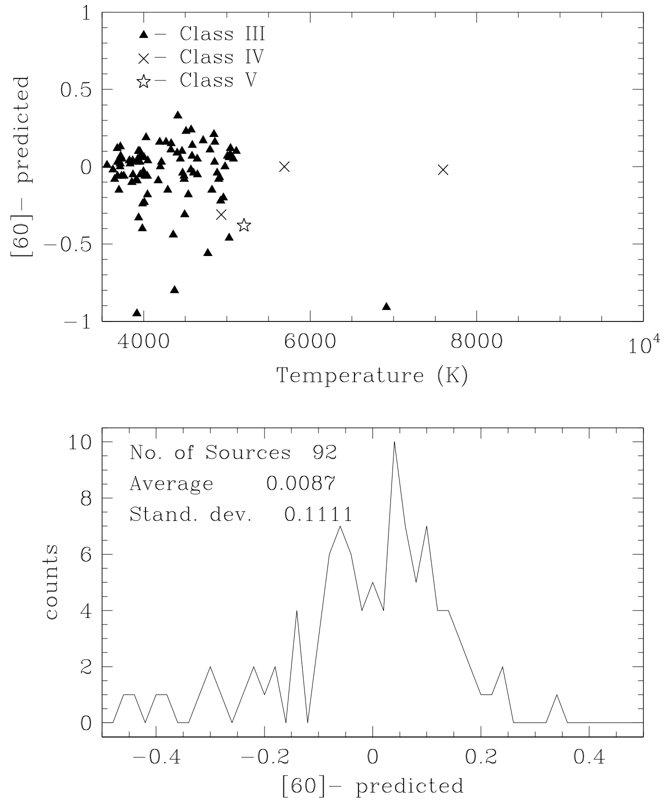

Figure 7. The difference between the measured and predicted magnitudes for $IRAS$ at 60 μm. The upper plot shows the difference with temperature and the lower shows the histogram of the distribution.

The 60 μm filter could only detect the brightest sources which were invariably the K and M giants. Also by 60 μm there are a significant number of sources with infrared excesses or for which there is background contamination. However the standard deviation between the measured and predicted magnitudes is only 0.11 magnitudes, and again dominated by error in the $IRAS$ measurements.

5.3. N AND Q PHOTOMETRY

As a more precise test, the calibration method was applied to N and Q bolometry obtained on the IRTF in 1992 (Hammersley et al. 1998). Figure 8 shows the difference between the measured and predicted magnitudes at 8.7 μm and Q. The 8.7 μm filter is a narrow-band filter near the deepest part of the SiO bands. Therefore, for the coolest stars there is a significant discrepancy between the measurement and the prediction. However, differences caused by the SiO show a clear trend with temperature. This indicates that, for a specific filter, the effect of the SiO can be calibrated against temperature. When the effect of the SiO is removed using a low order polynomial fit the standard deviation between the measured and predicted magnitudes at 8.7 μm drops to only 0.013 magnitude.

The Q–filter does not include any major bands and so there is no trend with temperature. However the signal-to-noise is lower and the standard deviation between the measurements and predictions is 0.035 magnitudes.

Also shown on the two plots, as open circles, are the differences between the measured magnitudes and those predicted using the Cohen templates. As the templates are based on measured spectra the SiO is included and so there is no trend with temperature in the 8.7 μm plot. There are Cohen templates for nine of the stars measured in the five IRTF filters. Averaging all these points suggests that the difference in zero points between the templates and the model SEDs is at most 1%.

6. LESSONS LEARNED

This proved to be a large project, with in the end a large number of people involved. In general the project progressed well and two factors which helped considerably in this were:

- from the start, the ISO-GBPPwg included experts in all of the necessary fields. Having the experts saved a lot of time and meant that the project progressed in the correct direction from the beginning
- the calibration project began sufficiently before launch that we were able to meet the main delivery dates. It should be

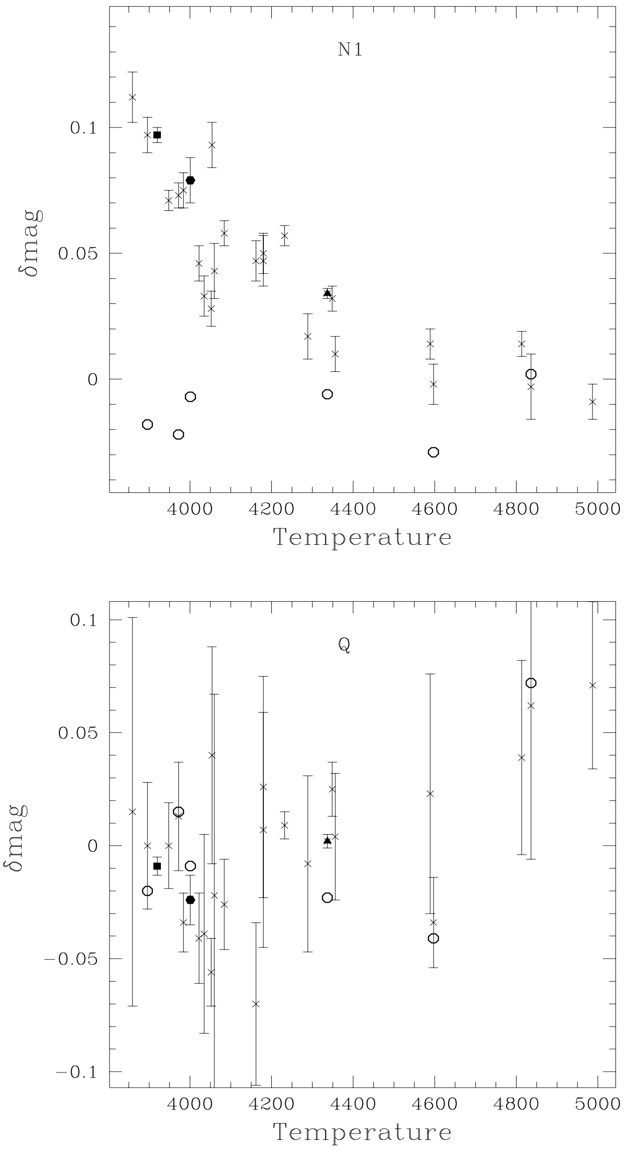

Figure 8. The difference between the measured and predicted magnitudes at 8.7 μm (N1) and Q including the error bars on the measurements. The open circles show the difference between the measured and predicted magnitudes using the Cohen templates.

noted that this sort of project takes a minimum of 4 to 5 years and cannot be rushed.

There were however some areas that could be improved:

– communications between the groups, particularly with the instrument teams, on occasion were lacking. Whilst the reasons for this are understandable, more specific inputs from the instruments could have been valuable early on
– for various reasons it proved difficult to find funding for personell, particularly for the day-to-day tasks. This placed a considerable extra burden on certain members of the team, which did delay certain stages of the project.

7. CONCLUSIONS

The ISO-GBPPwg was created to deliver a stellar calibration data base which would provide the basis for the photometric calibration of ISO between 2.4 and about 50 μm. A method of producing SEDs based upon near infrared photometry and stellar models was developed, which was then tested against observations over a wide wavelength range. The delivered SEDs were used by the instrument dedicated teams and, as far as the authors have been able to ascertain, few problems have been found with the accuracy of the predictions.

The ISO-GBPPwg was able to deliver a uniform calibration data base, with sources covering the whole sky, on time, and with an accuracy typically two to three times better than was originally requested.

ACKNOWLEDGEMENTS

The authors wish to thank all those who contributed to the ISO-GBPPwg without whose efforts the project would not have been possible, in particular, H.J. Habing, M. Selby, T. Lim, L. Metcalfe, A. Salama, M.F. Kessler, P. Bouchet, N. van der Bliek, J. Manfroid, D. Blackwell, T. Lynas-Gray, P. di Benedetto, B. Gustafsson, K. Erikson. We also wish to thank the ESO Observing Programmes Committee, the MPIfA, the NASA/IRTF and the Comisión de Asignación de Tiempo (Tenerife), for awarding sufficient observing time to undertake such a project.

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