Astron. Astrophys. 128, 84–93 (1983)

ASTRONOMY AND ASTROPHYSICS

Near-infrared photometry

II. Intrinsic colours and the absolute calibration from one to five micron

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Received March 9, accepted June 16, 1983

Summary. We continue the description of our unification and reparametrization of results of various authors on near-infrared photometry, by deriving intrinsic colours and absolute calibration values for the photometric system described in a previous paper. We also supply a representative set of interstellar extinction parameters. Comparisons between the observed stellar colours and black bodies as well as current stellar models are included when helpful or illustrative. The present series of papers enhances the Arizona photometric system as defined by Johnson in the early nineteen-sixties.

Key words: near-infrared – intrinsic colours – absolute calibration

I. Introduction

Only a few years after the conception of the near infrared photometric (Arizona-) system (Johnson, 1964), Johnson published his 1966 review titled "Infrared Photometry". There he discussed a number of subjects including the intrinsic colours of stars and their absolute fluxes. In 1968 he summarized the then current knowledge of interstellar extinction. In the meantime, many more one to five micron photometric observations have become available and Johnson's extensive discussion on the subject of regional variations of interstellar extinction has been largely superseded. Additionally, since 1966 considerable work was done on the absolute calibration of near infrared photometry, so better references on this subject are now available. These investigations will be discussed here (Sect. II).

On the subject of intrinsic colours, however, Johnson (1966) remains the only comprehensive reference. But his tables, which list J, K, L (M) intrinsic colours as a function of spectral type and luminosity class are no longer current. First, Johnson did not use the band centered at 1.65 μm (H), which is now in widespread usage. In addition, intrinsic colours for limited ranges of spectral types and/or luminosity (e.g. late type giants) by several authors should be preferred over Johnson's values. In some cases, these newer data are not (quite) on the Arizona system and need to be transformed before a merging can be effected. In a previous paper (Koornneef, 1983, hereafter called Paper I), such a merging process was performed for observational data from various sources and in the present paper we will make extensive use of the results presented there.

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II. Absolute calibration

Since the initial determination of the absolute calibration from one to five micron by Johnson (1965), several authors have rediscussed the subject. Apart from a paper by Labs and Neckel (1968), which deals with the flux distribution of the Sun, none of the published calibrations report any absolute measurements. The procedures used by the various authors have been reviewed by Hayes (1979) and will not be repeated here except to mention that all papers adopt one or more of the following assumptions:

– the energy distribution of α Lyr can be approximated by a black body

– the energy distribution of α Lyr can be approximated by a stellar model

– the energy distribution of a certain star (or group of stars) is identical to that of the Sun.

In the following (Sect. IIa) we argue that an absolute calibration as published for one photometric system cannot be directly adopted for another one without further scrutiny.

In Sect. IIb we introduce a novel way of using the observed photometric sequences to adapt absolute calibrations derived for a different system.

a) Can any of the published calibrations be used?

Since modern calibrations (e.g. Wamsteker, 1981) claim an accuracy of about 4% or better, it is no longer possible to compare results from different authors (i.e. different photometric systems) without specifically discussing the zero-points and effective wavelengths of the systems adopted.

The question of the zero-points is in principle straightforward. Some systems assume that α Lyr has either zero magnitudes or zero colours at all wavelengths (cf. Thomas et al., 1973; Elias et al., 1982) although at first glance this is confusing because the V magnitude of α Lyr is not equal to zero. Johnson et al. (1966) used a certain set (rather than just one) of A0 main sequence stars to define the zero-point and, not surprisingly, found non-zero colours for α Lyr. Actually, the Johnson system is now usually regarded as defined by the whole body of his work rather than by specific stars or a single "primary" standard. Such a primary standard may (HR 3314: Jones and Hyland, 1982) or may not (α Lyr) be observable from both hemispheres but is certainly not accessible during every observing run. The system for which at present we wish to find a suitable calibration was created by merging data from many different sources, and as shown in Paper I, zero-point differences of up to 0.05 mag exist between the various data sets. We adopt the pragmatic view that the properties of our photometric system, including its zero-point, are defined by the whole data-set.

A more complicated issue is that of effective wavelengths. Transformation equations, such as those given in Paper I, will typically (but not always) tell whether the effective wavelength of a certain bandpass-filter is longward or shortward of the filter adopted in another system but not by how much (at least not without further assumptions). Laboratory passbands, when available, do not help much as they are not usually available with sufficient accuracy (and almost never at operating temperature and convolved with the detector responsivity function). In addition, atmospheric transparency profiles (cf. Manduca and Bell, 1979; Mountain et al., 1982) and red leaks affect the overall filter characteristics. This area obviously needs further attention but for the time being we will have to make the usual, but almost certainly wrong, assumption that the effective wavelengths of the data of Paper I are exactly at their "canonical" values of 1.25, 1.65, 2.2, 3.6, and 4.8 μm, respectively (J, H, K, L, and M). This assumption unjustly but unavoidably forces "non-canonical" effective wavelengths on filters which show non-unity transformation coefficients with respect to the data of Paper I. Estimations of effective wavelengths for other systems can be readily derived only under the assumption that stars behave like black bodies. Although therefore of limited validity, the following numbers serve to give at least a qualitative feeling for typical shifts in effective wavelengths. From the transformation coefficients derived in Paper I we conclude that the effective wavelengths, relative to the values given above, of the filters used by Engels et al. (1981) were 1.256, 1.58, and 2.10 μm for J, H, and K, respectively. Similarly, we find 1.23 and 2.14 μm for the J and K filters of Glass (1974). In addition, the well publicized (e.g. Jones and Hyland, 1982) transformation coefficient of 1.07 between the Mount Stromlo ⟨MSO⟩ and Anglo-Australian ⟨AAO⟩ $(J-H)$-colours can be explained if the ⟨AAO⟩ J-filter is at a wavelength only 0.03 μm smaller than that of the ⟨MSO⟩ J-filter, assuming that the respective H-filters are identical.

We conclude that none of the previously published absolute calibrations can be used without any modification.

b) *Adapt published calibrations to the data set of Paper I*

As can be seen Fig. 1, the general behaviour of the stellar measures as a function of temperature differs considerably from that of black bodies. However, for the hotter stars the observed slope of the stellar sequence in the various colour-colour diagrams is very close to the slope of the black body loci. This observation concurs with the theory of stellar atmospheres but is nevertheless important as the present evidence is purely experimental. In addition, Sect. IIIa shows that theoretical fluxes for hot stars through the V, J, H, K, L, and M-bands can be accurately fitted with a single black body. We conclude that it is reasonable to require of a set of absolute calibration parameters that it yields fluxes which can be (best-) fitted with a single black body as long as the star is earlier than approximately B7 (see Fig. 1). In the following we investigate which of the published calibrations yield hot star flux-distributions most closely resembling those of black bodies.

Rather than just use the measurements of a single hot star, we represent all measurements (of Paper I) which are on the high temperature tail by a best-fit line (the "hot-line") parallel to the black body line. The perpendicular projection of the origin on the "hot-line" has the following components:

$$(V-J, V-H, V-K, V-L, V-M)$$
$$=0.00,\ 0.00,\ 0.025,\ 0.045,\ 0.045).$$

Those coordinates define a fictitious hot star, which we name the "Not-star", and which we use as a base point for black body fits. Note that these values provide a convenient representation of the zero-point of our photometric system.

Calibration parameters as needed to convert the colours of the Not-star to flux-ratios were taken from a variety of sources. For V, we used the calibration by Hayes and Latham (1975) and Hayes (1979). For the infrared bands the following references were used: Johnson (1965), Wilson et al. (1972), Thomas et al. (1973), Gehrz et al. (1974), Hayes (1979), and Wamsteker (1981). The most recent of these references (Wamsteker, 1981) gives the absolute calibration for the photometric system of Engels et al. (1981). The relation between their system and that of Paper I is very well known so that the appropriate corrections for zero-point and effective wavelength differences can be easily performed. The best fit black body for the Not-star with this calibration has a temperature of 11,000 K with all deviations less than 2%. That is well within the estimated accuracy of the absolute calibration of about 4% (Wamsteker, 1981). Fluxes calculated with the older absolute calibrations do lead to a poorer quality black body fits. The Johnson (1965) near infrared calibration, for example, leads to a colour temperature of the Not-star of 10,200 K from $(V-J)$ and 11,700 K from $(V-K)$. A 1% change in calibration corresponds to a change in colour temperature of about 100 K. These colour temperatures are still compatible with the 11,000 K value from Wamsteker's calibration and with Johnson's (1965) statement that his calibration values are "unlikely to be in error by more than 10%". The other references given are also compatible to within the quoted errors with a 11,000 K Not-star but uncertainty with respect to the required zero-point and wavelength transformations make these references less useful for our present purposes. Nevertheless, adopting 11,000 K as an appropriate temperature for the Not-star is thus in excellent agreement with all published calibrations.

The combination of the colours of the Not-star, its colour temperature of 11,000 K and the absolute calibration of the V-band now directly lead to the absolute calibration constants shown in Table 1. This calibration has the following properties:

– it is specifically traceable to Wamsteker's (1981) calibration to well within its error bars of 4%;

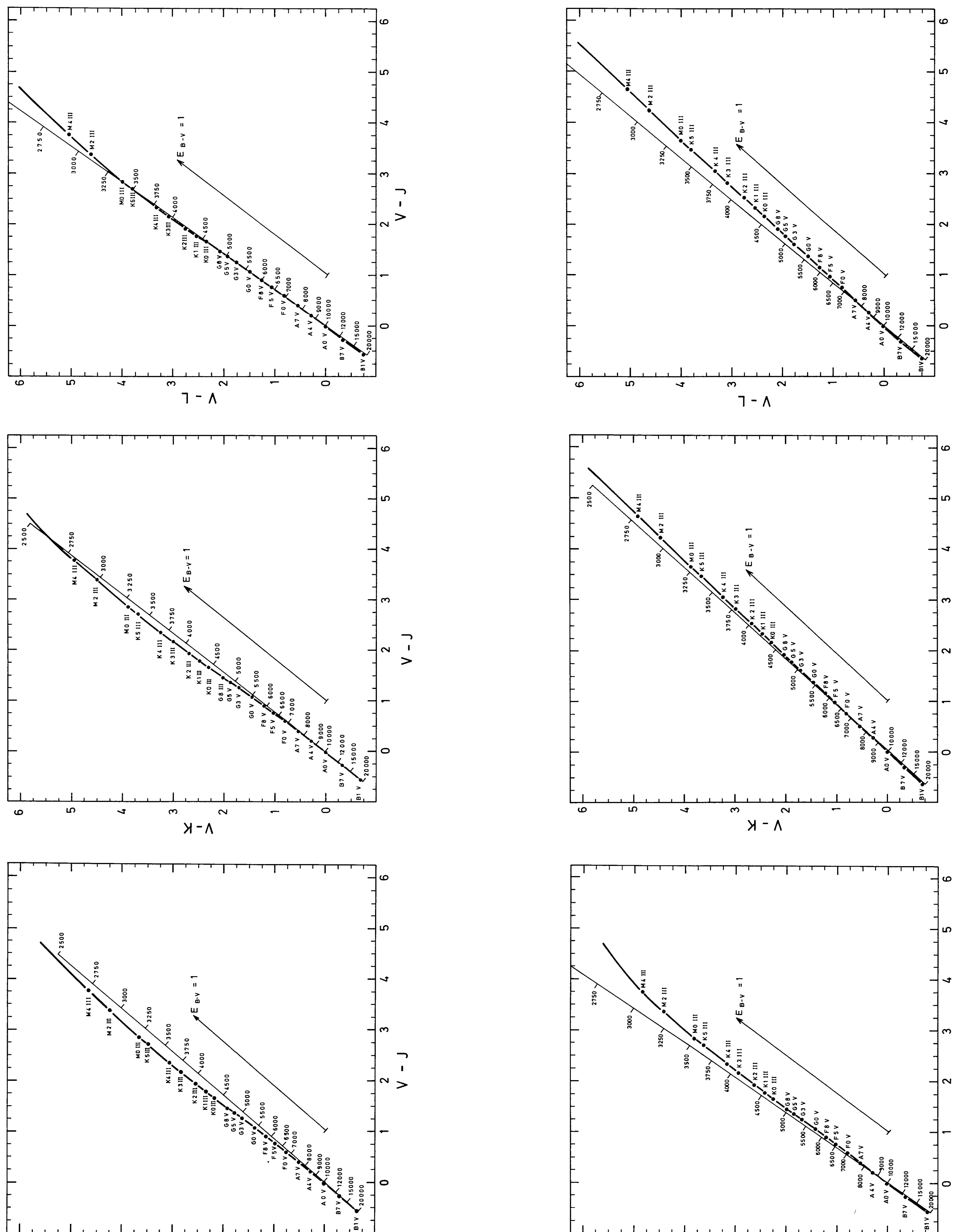
– when applied to the measurements of sufficiently hot (main sequence) stars, the resulting flux distribution can be exactly fitted by a single black body.

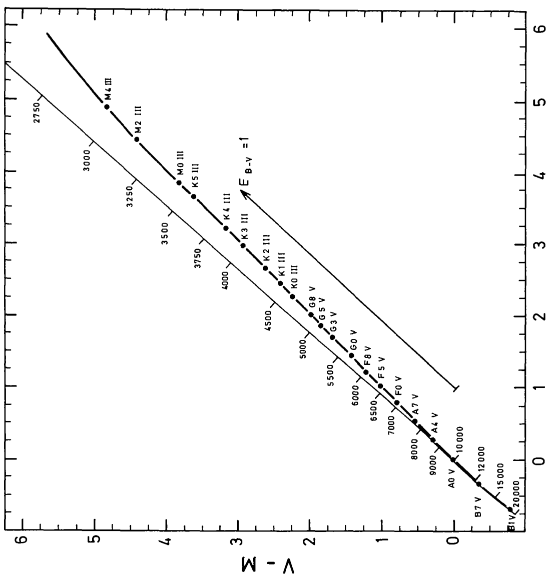
Table 1. Absolute flux density for zero magnitude

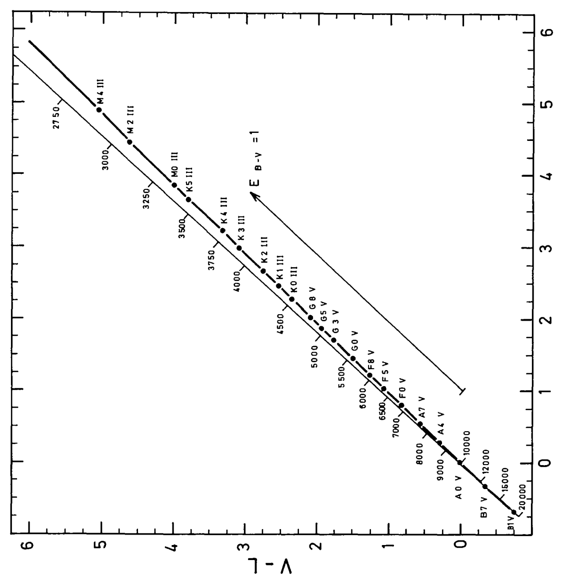
Band	Wavelength	F_λ (W cm^{-2} μm^{-1})	F_ν (W m^{-2} Hz^{-1})	Jy
J	1.25 μm	3.14 × E-13	1.64 × E-23	1635
H	1.65 μm	1.20 × E-13	1.09 × E-23	1090
K	2.2 μm	4.12 × E-14	6.65 × E-24	665
L	3.6 μm	6.41 × E-15	2.77 × E-24	277
M	4.8 μm	2.13 × E-15	1.64 × E-24	164

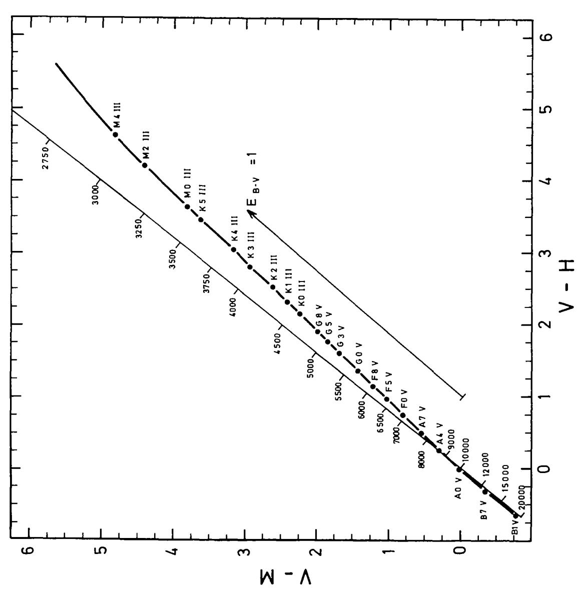
c) *What are the colours of the Sun?*

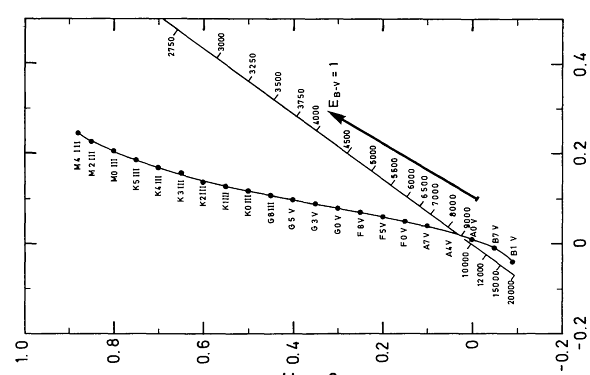
The absolute flux distribution of the Sun is given by Labs and Neckel (1968) on intervals rather narrower than the widths of the


V - L
V - J
V - K
V - J
V - H
V - J
V - L
V - H
V - K
V - H
V - M
V - J
$E_{B-V} = 1$









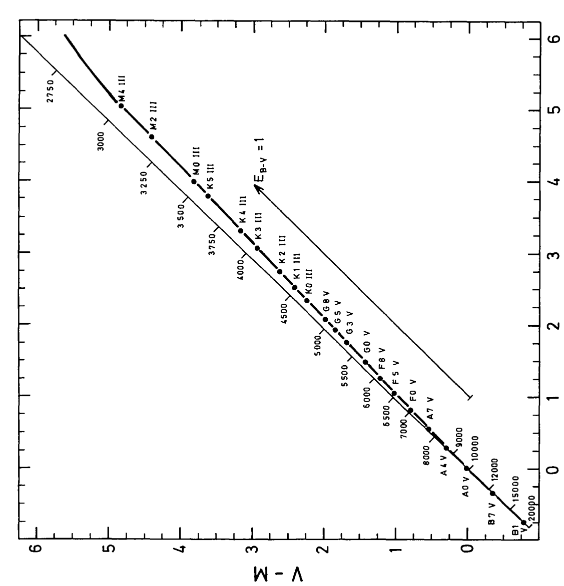


Fig. 1. These colour-colour diagrams show the average stellar sequences derived from the data of Paper I. Black body lines and reddening vectors are also shown

Table 2. Flux, in W cm^{-2} μm^{-1}, for a G-dwarf of magnitude K

$1.4<\lambda<1.86$ μm:	$F_\lambda = 1.34\ 10^{-13} 10^{-0.4\mathbf{K}} (\lambda^2 - 4.82\lambda + 6.068)$
$1.9<\lambda<2.6$ μm:	$F_\lambda = 7.21\ 10^{-13} 10^{-0.4\mathbf{K}} \cdot \lambda^{-3.63}$
$2.7<\lambda<4.2$ μm:	$F_\lambda = 9.95\ 10^{-13} 10^{-0.4\mathbf{K}} \cdot \lambda^{-3.91}$

near-infrared photometric filters. Wamsteker (1981) has convolved the Labs and Neckel data with some reasonable passbands and lists the results in his table 4 (Columns 4 and 5). These absolute fluxes through the various filters can be directly converted to photometric colours of the Sun on the system of Paper I by use of the flux to magnitude conversion factor given above. We find the following values:

$$(V-J, \ldots, V-M) = (1.12, 1.42, 1.49, 1.52, 1.50).$$

A comparison of these colours with the G main sequence star data of Table 2 of Paper I shows that the solar values are in excellent agreement with the stellar data in the sense that they are within 0.01 mag of the regression line through the G main sequence star data which passes through

$$(V-J, \ldots, V-M) = (1.12, 1.42, 1.49, 1.53, 1.49).$$

These solar colours are somewhat redder than the G2V intrinsic colours of Johnson (1965, 1966). This is in agreement with the findings of Hayes (1979), who argues that the Sun is photometrically more like G4V rather than the spectroscopic type G2V. Such effects appear to be rather more general as the G main sequence star data of Paper I show a very large range in colour for every spectral type which is very possibly at least partly intrinsic. The near-infrared colours of 24 (of which only 8 are in common with Paper I) main sequence stars ranging from G1 to G5 given by Allen (1981) seem to support this conclusion.

d) Absolute calibration of spectrophotometry

As pointed out by Allen (1981), who uses a photometric system very similar to ours (see Paper I), it is convenient to use G main sequence stars for the flux calibration of spectrophotometric observations. He provides three simple formulae for the wavelength regions of 1.4–1.86 μm, 1.9–2.6 μm, and 2.7–4.2 μm, respectively. These formulae predict the flux for a typical G main sequence star at a given wavelength if its K (2.2 μm) magnitude is given. As the typical colours for a G main sequence star are $H-K=0.07$ and $K-L=0.04$, we can recover the absolute calibration at H, K, and L used by Allen for the derivation of his formulae. The values found are typically 6% lower than those of Table 1. In order to provide compatibility between the flux calibrations of wide band photometry and (CVF) spectrophotometry, Allen's formulae are reproduced here as Table 2 with their multiplicative constants adapted to the calibration of Table 1:

III. Some comparisons with stellar models

The smoothed data of Table 3 of Paper I, schematically represented here as Fig. 1, provide a convenient basis for a comparison with stellar models. In particular, we studied the models provided by Kurucz (1979). It should be noted that Kurucz does not make great claims for the accuracy of his models in the infrared. In particular, opacities for diatomic molecular lines are not included. Also, his infrared fluxes longward of 1.69 μm are tabulated at rather large wavelength intervals. The coolest model tabulated has an effective temperature of 5500 K. Nevertheless, some comparisons between models and observations can be made which give some interesting results.

a) Do hot-star-models look like black bodies?

We argued previously that the observations of hot stars suggest that the near infrared colours with respect to V behave like those of black bodies. In order to check this observation against the models, we took the fluxes at 0.5475, 1.245, 1.65, 1.8, 2.7, 4.0, and 5.0 μm for an 18,000 K, $\log g = 4$ model from Kurucz (1979). Colour temperatures were calculated for all infrared wavelengths with respect to the visual (0.5475 μm). The average colour temperature found this way was 21,250 K. A black body with this temperature fitted at V, will actually approximate the near-infrared data within 0.4% r.m.s. Hence our claim appears to be substantiated. The difference between the effective (18,000 K) and colour (21,250 K) temperature corresponds to what Johnson (1965) describes as a "drop in brightness temperature at the long wavelengths" and is also known as "backwarming".

b) Some comments on the $(J-H, H-K)$ *diagram*

The observed stellar sequence of the $(J-H, H-K)$ diagram of Fig. 1 is very well defined (see Paper I) and has a "smooth" shape. Note that similar sequences in the literature (e.g. Aaronson and Mould, 1982; Jones and Hyland, 1982) are more "jagged", which we think is due to insufficient statistics. The data of Paper I yield an average slope of 4, whereas the maximum slope values slightly in excess of 5, which occurs between spectral types A7 and K2. The black body line which is also shown in this figure has an almost constant slope of only 1.4. The deviations from black body behaviour are obviously very pronounced in this diagram. This results mainly through the minimum in the H^- opacities, which occurs around 1.8 μm (e.g. Gingerich and Kumar, 1964; Allen, 1973). A synthetic $(J-H, H-K)$ diagram was constructed (not shown) on the basis of the data in Kurucz (1979). No convolution of the tabulated data with filter passbands was attempted and data at 1.25 and 2.2 μm had to be interpolated from nearby wavelengths. Nevertheless, this simplified approach showed very convincingly that the models in fact mimic the observed sequence in the $(J-H, H-K)$ diagram. For stars hotter than 10,000 K, the slope of the model sequence is close to the black body slope, whereas a sharp knee occurs between 10,000 and 8000 K. For cooler stars, the model data show a slope of almost seven. This value is well in excess of the observed slope but that might very well be due to the adoption of "monochromatic" fluxes at 1.25, 1.65, and 2.2 μm, rather than values properly convolved with the passbands.

This, indirectly, raises another issue, namely that of bandwidth effects. The rather pronounced variations in the opacities within the passband of the H filter should cause strongly non-linear energy distributions for cool stars. One would thus expect the effective wavelength of the H filter to be more strongly dependent on spectral type than for the other filters. Therefore, it is no great surprise that rather substantial transformations can occur for colours involving the H filter (e.g. Paper I, Aaronson and Mould, 1982; Griersmith et al., 1982). Bandwidth effects could also produce different results for interstellar extinction determinations depending on the spectral types of the stars used (also see Sect. V).

c) The observations, the models, and black bodies

The wavelength intervals at which Kurucz (1979) tabulates model fluxes are very widely spaced beyond 1.69 µm. Between that value and 5 µm, the only fluxes given are those at 1.8, 2.7, and 4 µm. The possibilities to compare models and observations beyond the *K*-band are therefore very limited.

One set of calculations was done to compare the models directly with black bodies at 2.7, 4, and 5 µm. Various colour-colour diagrams were constructed in which both the black body lines and the models were shown. The conclusion reached was that the differences between the models and the black bodies are much smaller than the differences between the observations and black bodies. For example, the models gave $d(V-\lambda_1)/d(V-\lambda_2)>1$ for all $\lambda_1>\lambda_2$, as do black bodies, whereas the observed (Paper I) value for $d(V-M)/d(V-L)$ is significantly smaller than one. In agreement with the statement of Kurucz (1979), his present models are not very satisfactory for cool stars at the longer near-infrared wavelengths. We do not pursue this comparison any further.

Black bodies find rather extensive use in the literature as an approximation for stellar energy distributions, for example when infrared excesses due to free-free or thermal dust radiation are sought. Such applications of black bodies on near-infrared photometric data require extreme caution as the differences between the stellar data and black bodies are substantial (Fig. 1). In fact, these differences can be even more pronounced than this graph may suggest at first sight. A good example is the $(V-L, V-J)$ diagram of Fig. 1. The stellar sequence shown there almost coincides with the black body line for the whole spectral range down to M0III ($T=3400$ K). However, this does not imply that the stars have the temperatures suggested by this diagram, at least not in any simple meaningful way. Rather, it just so happens that the relative opacities as a function of effective temperature keep the $V-L/V-J$ ratio on the black body line. To take one case a little further, the $(V-L, V-J)$ diagram would suggest a temperature of 3500 K for a K5 giant. A black body with that temperature would obviously give an encouragingly nice fit to the *V*, *J*, and *L* observations of such a star. But the H and K data points would lie above (0.3 and 0.2 mag, respectively) and the *M* (5 µm) point below (by 0.3 mag) this black body curve. It would be a naive mistake to interpret this as an excess at H and K and a deficiency at M.

IV. The intrinsic colours

As mentioned in the Introduction, the tables with intrinsic stellar colours of Johnson (1966) can no longer be considered satisfactory. But the data base supplied in our earlier paper as well as various other references allow for a substantial improvement. In the following we describe how the various references can contribute to this purpose.

Much use will be made of the observational data as well as the transformation equations of Paper I. But due to various selection effects, these data do not include enough supergiants to derive their intrinsic colours. Also, Paper I does not give any data for late type main sequence stars. The five micron (*M*) photometric data of Paper I, supplemented by those of the appendix to the present paper, cover a larger range in spectral type and luminosity than any other published collection of bright star photometry in this band. Nevertheless, due to their relatively poor photometric accuracy as well as selection effects, the intrinsic colours involving the M-band remain relatively poorly determined although some improvement over the Johnson (1966) values can be acheived.

Very useful are the (J, H, K, L) intrinsic colours of M-type giants and supergiants by Lee (1970). His data are on the Johnson-system and we have confirmed this by comparing his values for giant stars with Paper I. The intrinsic colours given by him for M-type supergiants could thus be directly applied to the present photometric system. No data for the five micron photometric band were provided by Lee, so that we are restricted to the data of Paper I.

The only specialized tabulation of intrinsic colours of late type dwarfs is by Frogel et al. (1978) and includes *J*, *H*, and *K* values only. Unfortunately, the photometric system employed by them is rather different from Johnson's (and ours). We could nevertheless transform their data to the present system basically by conserving the differences between main sequence and giant colours implied by their tables. The *L* and *M*-colours of late type main sequence stars remain uncertain as neither Frogel et al. nor Paper I provide data for those bands.

Intrinsic colours (*J*, *H*, *K*, and *L*) for early type main sequence stars as well as supergiants have been published by Whittet and van Breda (1980). Their data could be directly transformed to our system as the relation between the photometric system of Glass (1974), which was adopted by Whittet and van Breda, and the present system is very accurately known (see Paper I). A modest amount of smoothing was applied to the Whittet and van Breda results in agreement with the advice of van Breda (1982, private communication).

The intrinsic colours as proposed for the photometric system of Paper I are given as Tables 3–5. The determination of the values shown there has gone through various steps. First of all we have determined reasonable values for $V-K$ as a function of spectral type for each of the three luminosity classes. After this, spectral types as given by the various authors have been completely disregarded and only relations between $V-K$ and the other colours under consideration have been taken into account. The reason for this procedure is that the colour-colour relations were found to be much more similar between authors than the colour-spectral type relationships. A detailed description of the various steps followed is given below.

A. $V-K$ vs. spectral-type

a) Main sequence stars

For the earliest main sequence stars (up to A2) we used the $V-K$ values of Johnson (1966) combined with those of Whittet and van Breda (1980). The $V-K$ value for A0 was forced to agree with the value of Paper I. From A2–F2 the Johnson values were adopted. From G5 (and later) we used the $V-K$ values of Frogel et al. (1980). To provide a smooth transition to the Johnson data for the earlier stars, interpolated values were adopted for F5–G5 in such a way that the solar colours derived in the present paper (Sect. IIIc) were adopted for G3V.

b) Giants

$V-K$ values for the giant stars were taken from Johnson for spectral types up to K5. The later (M-type) giant colours are from Lee (1970).

c) Supergiants

For the supergiants up to A2, a smoothed difference was calculated between the main sequence and supergiant $V-K$ values of Whittet and van Breda. This difference was applied to the $V-K$ colours for the dwarfs as derived above. For stars between A5 and K5, the $V-K$ values of Johnson are given. For the same spectral

Table 3. Intrinsic colours for main sequence stars

Sp.	V-K	J-K	H-K	K-L	K-M
O6-8	-0.93	-0.21	-0.05	-0.04	
O9	-0.89	-0.19	-0.05	-0.03	
O9.5	-0.87	-0.18	-0.05	-0.03	
B0	-0.85	-0.17	-0.05	-0.03	
B0.5	-0.79	-0.15	-0.04	-0.02	
B1	-0.76	-0.14	-0.14	-0.02	
B2	-0.67	-0.13	-0.04	-0.02	-0.08
B3	-0.57	-0.11	-0.03	-0.02	-0.07
B4	-0.50	-0.10	-0.03	-0.02	-0.06
B5	-0.43	-0.08	-0.02	-0.01	-0.05
B6	-0.37	-0.07	-0.02	-0.01	-0.04
B7	-0.30	-0.05	-0.02	-0.01	-0.03
B8	-0.25	-0.04	-0.01	-0.01	-0.02
B9	-0.14	-0.02	-0.01	0.00	-0.01
A0	0.00	0.01	0.00	0.00	0.00
A1	0.06	0.02	0.00	0.00	0.00
A2	0.13	0.04	0.01	0.00	0.00
A3	0.20	0.05	0.01	0.01	0.00
A4	0.28	0.07	0.02	0.01	-0.01
A5	0.35	0.09	0.02	0.01	-0.01
A6	0.40	0.10	0.02	0.01	-0.01
A7	0.45	0.12	0.02	0.01	-0.01
A8	0.56	0.14	0.03	0.02	-0.02
A9	0.68	0.17	0.04	0.02	-0.02
F0	0.79	0.20	0.04	0.02	-0.02
F2	0.93	0.24	0.05	0.03	-0.03
F5	1.01	0.26	0.06	0.03	-0.03
F8	1.12	0.29	0.06	0.03	-0.03
G0	1.22	0.31	0.07	0.04	-0.03
G3	1.49	0.37	0.08	0.04	-0.04
G8	1.60	0.41	0.09	0.05	-0.04
K0	1.75	0.47	0.10	0.05	-0.04
K1	2.00	0.54	0.11	0.05	-0.04
K2	2.25	0.62	0.13	0.06	
K3	2.50	0.67	0.14	0.07	
K4	2.75	0.72	0.15	0.08	
K5	3.00	0.77	0.16	0.10	
M0	3.25	0.83	0.18	0.13	
M1	3.50	0.86	0.19	0.15	
M2	3.75	0.89	0.21	0.15	
M3	4.00	0.92	0.26	0.16	
M4	4.25	0.90	0.28	0.16	
M5	4.50	0.90	0.29	0.18	
M6	4.75	0.88	0.30		
M7	5.00	0.89	0.31		
M8	5.25	0.90	0.33		
	5.50	0.92	0.34		
	5.75	0.95	0.36		
	6.00	0.98	0.37		
	6.25	1.01	0.38		
	6.50	1.05	0.40		
	6.75	1.09	0.41		
	7.00	1.11	0.42		
	7.25	1.14	0.43		

Table 4. Intrinsic colours for giant stars

Sp.	V-K	J-K	H-K	K-L	K-M
G3	2.08	0.56	0.11	0.06	-0.04
G8	2.16	0.59	0.12	0.07	-0.05
K0	2.35	0.64	0.13	0.07	-0.06
K1	2.48	0.68	0.14	0.08	-0.07
K2	2.59	0.72	0.14	0.08	-0.08
K3	2.92	0.80	0.16	0.09	-0.08
K4	3.24	0.88	0.18	0.10	-0.09
K5	3.67	0.96	0.20	0.11	-0.09
M0	3.74	0.97	0.21	0.12	-0.09
M1	3.90	1.01	0.21	0.12	-0.09
M2	4.16	1.04	0.23	0.13	-0.09
M3	4.63	1.10	0.25	0.14	-0.09
M4	5.34	1.16	0.27	0.17	-0.08
M5	6.20	1.24	0.31	0.19	
M6	7.20	1.30	0.35	0.25	

Table 5. Intrinsic colours for supergiant stars

Sp.	V-K	J-K	H-K	K-L	K-M
O9	-0.82	-0.13	-0.06	-0.08	
O9.5	-0.76	-0.12	-0.05	-0.07	
B0	-0.70	-0.11	-0.04	-0.07	
B0.5	-0.61	-0.10	-0.04	-0.07	
B1	-0.55	-0.09	-0.03	-0.07	
B2	-0.40	-0.07	-0.03	-0.07	
B3	-0.28	-0.04	-0.03	-0.05	
B4	-0.20	-0.02	-0.02	-0.01	
B5	-0.13	0.00	-0.01	0.02	
B6	-0.07	0.02	0.00	0.03	
B7	0.00	0.04	0.00	0.04	
B8	0.04	0.05	0.00	0.05	
B9	0.11	0.07	0.01	0.06	
A0	0.21	0.09	0.01	0.07	
A1	0.25	0.10	0.01	0.07	
A2	0.31	0.11	0.02	0.08	
A5	0.36	0.12	0.02	0.08	
F0	0.63	0.18	0.03	0.09	
F2	0.75	0.22	0.04	0.09	
F5	0.93	0.27	0.05	0.10	
F8	1.21	0.35	0.07	0.10	
G0	1.44	0.41	0.08	0.11	
G3	1.67	0.47	0.09	0.11	
G8	1.99	0.54	0.11	0.12	
K0	2.16	0.58	0.12	0.13	-0.05
K1	2.29	0.62	0.13	0.14	-0.06
K2	2.44	0.65	0.13	0.15	-0.07
K3	2.72	0.72	0.15	0.16	-0.08
K4	3.00	0.79	0.17	0.17	-0.08
K5	3.70	0.96	0.20	0.18	-0.09
M0	3.82	0.99	0.21	0.19	-0.09
M1	3.98	1.00	0.22	0.19	-0.09
M2	4.31	1.06	0.25	0.20	-0.09
M3	4.91	1.16	0.28	0.22	-0.09
M4	5.52	1.20	0.28	0.23	
M5	6.30	1.30	0.32		

type, supergiants are increasingly redder than dwarfs by up to 0.3 mag at B7. The difference then decreases and is close to zero around spectra type A5. According to Johnson, the supergiants are then bluer up to the F-types whereas for G and later, the supergiants are redder again in increasing amounts. For the M-type supergiants, the $V-K$ values from Lee (1970) were adopted.

B. $J-K$ as a function of $V-K$

a) Main sequence stars

The adopted $J-K$ colours are typically a little redder than those by Johnson as both the data of Paper I and the transformed data of Whittet and van Breda indicate. For the latest type main sequence stars, we transformed the data of Frogel et al. (1980) using the equation derived below from the giant-data. The required corrections go up to 0.12 mag where the untransformed data are bluer.

b) Giants

The large abundance of data for giant stars allows for an accurate determination of their intrinsic colours. The giant $J-K$ colours as they follow from Paper I are virtually identical to those by Johnson for $V-K$ up to 4. For stars redder than that there is very good agreement between the data of Paper I and those by Lee (1970). The data by Johnson for this colour range are up to 0.2 mag bluer, which was assumed to be erroneous. Frogel et al. (1980) also provide giant colours but those are derived from the values by Johnson and Lee. The transformation between the present system and that by Frogel et al. can be recovered from these parallel data and is: $J-K=(J-K)_F+0.014(V-K)+0.025$. This equation was used to transform the intrinsic colours for late type dwarfs as given by Frogel et al. (1978) to the present system (see above).

c) Supergiants

The $J-K$ colours for the early type supergiants are those from Whittet and van Breda with small corrections due to the required transformation. The reddest supergiant colours come from Lee (1970) without any modification. These values are approximately 0.2 mag redder than those by Johnson. However, the Johnson colours for intermediate spectral types (F0–K5I) fit nicely between the Whittet and van Breda and the Lee data.

C. $H-K$ as a function of $V-K$

a) Main sequence stars

For the earliest main sequence stars, $H-K$ was found from the data of Paper I and those by Whittet and van Breda which were in good agreement. The $H-K$ values for the redder stars are those by Frogel et al. but corrected by 0.05 mag as follows from the giant colours.

b) Giant stars

The $H-K$ values for the giants follow directly from the data of Paper I. These values are 0.05 mag redder than those by Frogel et al. (1978) (also see directly above) and 0.02 mag redder than those by Lee (1970) (see below).

c) Supergiants

For the supergiants up to M, the various references show the same $V-K/H-K$ relation as for the main sequence stars. For the M-supergiants, the Lee values were adopted but reddened by 0.02 mag (see above).

D. $K-L$ as a function of $V-K$

$K-L$ values for the bluer stars as well as for the giants were taken from Paper I. The adopted values for the redder dwarfs are from Johnson but bluer by 0.04 mag due to the change in zero-point of the L-band (see Paper I). This shift is also found from the Lee-data for the colour range in common. The supergiant colours by Lee are thus also blued by 0.04 mag. For the blue supergiants, the transformed data by Whittet and van Breda were adopted.

E. $K-M$ as a function of $V-K$

The $K-M$ values of the Tables 3–5 are incomplete as the available data do not suffice for the derivation of reliable intrinsic colours. Data are given only if they can be deduced directly from the data of Paper I (and the appendix to the present paper). Following Johnson, it was assumed that the $K-M$ values for giants and supergiants are identical for the colour ranges where data are entered.

V. Interstellar reddening

Some mention should be made of the problem of interstellar reddening in the near infrared. This subject is presently under active study after many years of tacit acceptance of "van de Hulst No. 15". A chronological list of some of the relevant references should include:

van de Hulst (1949)	theory; a.o. curve No. 15
Johnson (1968)	interpret van de Hulst, etc.
Lee (1970)	from M-supergiants
Hackwell and Gehrz (1974)	from supergiants
Schultz and Wiemer (1975)	O and B stars
Becklin et al. (1978)	for galactic centre
Elias (1978a)	Ophiuchis
Elias (1978b)	Taurus
Jones et al. (1980)	Coalsack
Jones and Hyland (1980)	Complilation
Tapia (1981)	on SAAO photometric system
Cohen et al. (1981)	on CIT system

No consensus has as yet been reached with respect to representative values for the general interstellar medium. But regions which have anomalous reddening have certainly been found (e.g. the Sco-Oph dark cloud).

Two different techniques have sofar been adopted for infrared extinction determinations. Several authors have used the traditional colour difference method. But early and late type stars generally give rather different results. It is not quite clear yet how this is to be interpreted because instrumental (bandwidth) effects are not easily sorted out. Other authors have interpreted colour-colour diagrams of heavily reddened fields. This has the advantage that very high extinction values can be reached. But the stars in these fields are usually too faint to obtain $E(B-V)$ so that normalization of the reddening curve is difficult. Also, spectral classification of all individual stars is not normally available so that some assumptions have to be made with respect to the stellar population of the field. Reddening slopes which are considerably different from the slopes of the observed stellar sequences ("temperature reddening") will be systematically biased in the direction of the temperature reddening unless the spread in intrinsic colours of the sample is somehow corrected for [e.g. $E(J-H)/E(H-K)$ should be sensitive to such errors].

In the light of the above difficulties it is impossible to reach an objective compromise on the results reported by the various authors. Additional technical complications arise from the wild variety of photometric systems in use as well as the fact that the transformation equations derived from stellar photometry (such as those given in Paper I) cannot be indiscriminately applied to extinction parameters (as is done by some authors). Also, as not all passbands were observed by all authors it was necessary to go through a certain amount of iteration. For example, it is possible to calculate E_{J-H}/E_{H-K} (as carefully derived by some authors) from E_{V-J}, E_{V-H}, and E_{V-K} (as tabulated), but not the other way around. In short, the values in Table 6 represent a personal, and therefore somewhat subjective, merging of what was thought to be the "best of" all quoted references.

Table 6. The adopted near-infrared reddening law

A_V/E_{B-V}	E_{B-V}	E_{V-J}	E_{V-H}	E_{V-K}	E_{V-L}	E_{V-M}
3.1	1	2.28	2.62	2.82	2.96	3.02

All other parameters in common usage (e.g. A_λ/A_V, E_{H-K}/E_{K-L}, etc.) can be derived from the above numbers. The value for E_{J-H}/E_{H-K}, probably the most controversial parameter, which follows from Table 6 equals 1.7. This number is a compromise between the Caltech results (Becklin et al., 1978; Cohen et al., 1981) and the higher values given by Jones and Hyland (1980) and Tapia (1981).

VI. Conclusions

All the near-infrared photometric systems currently in use at the major infrared observatories are natural systems. Measurements obtained with a specific instrument (filters, detector, etc.) are normally published without any colour transformations and often lack a uniquely defined zero point. Infrared photometry is now reaching the state of maturity where accuracies of one or two hundreths of a magnitude are routinely achieved and scientific programs which require that kind of precision are consequently being entertained. If such results are published in a natural system, it becomes unpractical to check the data or to use them as a basis for further work unless the photometric properties of that system in relation to others are exactly known. The need to transform natural data to a common system is thus becoming more and more relevant. The purpose of the present series of papers is to contribute towards that purpose.

In order to quality as a well defined and useful photometric system, several requirements should be satisfied. Most prominent ranks the availability of an extended and high quality data base. It is the data which have to define a system, as the usual technical information (filter curves, etc.) is not sufficient to produce a true "clone" of somebody else's photometric system (as has been amply demonstrated in optical photometry). All the major published collections of Southern stellar photometry known to the author have been merged and are available as Paper I (Koornneef, 1983). The system chosen is as close as practical to that by Johnson (1965) so that his measurements (Johnson et al., 1966) of Northern hemisphere stars, especially at J an K, supplement our data base. Note that all the transfomration information used to merge the various source catalogues into one homogeneous data set is included in Paper I.

The present paper provides information which should make the use of the photometric system of Paper I more practical. Data provided include stellar intrinsic colours and magnitude-flux conversion factors valid for the actual photometric system as well as a review of the interstellar extinction determinations.

Acknowledgements. Various colleagues have been kind enough to read earlier versions of this paper. Thanks are due to Drs. W. Eichendorf, D. Engels, I. S. Glass, J. Lub, and especially to Drs. J. C. Blades, A. Nijenhuis, and the referee, Dr. D. S. Hayes for constructive comments which improved the contents and/or presentation.

Appendix: M-measurements of 113 southern bright stars

HR	M	HR	M	HR	M	HR	M
33	3.70	1983	2.42	4102	3.17	6630	0.59
180	2.45	2015	3.72	4232	0.32	6879	1.75
188	−0.16	2020	3.51	4257	1.57	6913	0.51
322	1.38	2085	2.95	4357	2.25	6973	0.97
334	0.98	2227	1.12	4382	0.96	7150	0.97
434	1.65	2294	2.75	4517	0.13	7193	1.51
472	0.95	2421	1.86	4520	3.32	7234	0.63
489	1.36	2429	1.68	4630	0.16	7264	1.86
539	1.32	2451	3.51	4638	4.53	7340	3.41
585	0.24	2574	0.75	4662	2.87	7665	1.98
591	2.17	2701	2.58	4695	2.22	7773	4.81
612	5.00	2773	−0.93	4757	3.08	7869	0.89
740	3.69	2803	2.32	4786	0.70	7950	3.75
818	3.37	2845	2.96	4802	3.77	7980	0.31
841	2.23	2854	1.00	4825	1.87	7986	1.10
850	2.77	2970	1.65	4989	3.74	8167	2.29
874	1.48	2993	0.86	5020	0.96	8181	2.93
1136	1.46	3045	0.96	5028	2.67	8278	3.04
1208	−0.80	3314	3.99	5132	3.10	8414	0.91
1231	−0.78	3484	2.27	5249	4.67	8425	2.19
1318	2.36	3614	1.22	5287	0.75	8499	2.08
1326	1.43	3685	1.53	5315	1.10	8551	2.37
1336	1.40	3699	1.50	5487	2.88	8709	3.12
1453	2.28	3718	0.61	5531	2.41	8812	1.02
1464	1.74	3842	3.35	5649	1.38	8848	2.99
1543	2.15	3871	3.23	5685	2.88	8892	1.40
1654	−0.09	3903	2.01	6147	2.41		
1865	1.83	3994	1.44	6241	−0.09		
1948	2.29	4094	0.45	6378	2.47		

Of the 203 stars for which J, H, K, and L data were given in Paper I, M-data were available for only 87 stars (all taken from Engels et al., 1981). In the meantime, Engels (private communication) has measured an additional 113 stars at M with the 1-m telescope at La Silla. We reproduce his values in the above table with his kind permission.

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