Infrared Photometric Systems, Standards and Variability

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Abstract

The accuracy with which infrared photometry can be carried out is currently limited by poor definition of the instrumental system and by the accuracy of the available standard stars. We present new colour transformations between the CIT J, H, K photometric system and systems currently in use at Cerro Tololo, Mauna Kea and Kitt Peak. The precision of the J, H, K data for some of the stars observed by Elias *et al.* is improved and the system extended to fainter stars suitable for use with larger telescopes and/or infrared arrays. Evidence of infrared variability has been detected for one M dwarf star in our programme.

1. Introduction

In this paper we will describe the current status of J, H, K stellar photometry. The effective wavelengths of these passbands are $\sim 1.2\mu m, 1.6\mu m$ and $2.2\mu m$. At longer wavelengths the problems encountered are similar to, but worse than, those that we will be describing here. A useful review of JHKLM photometry is given by Bessell & Brett (1988).

For the last 10 years the pioneering work by Elias *et al.* (1982) has defined the most commonly used J, H, K photometric system (the CIT system), and provided the standard stars for infrared photometry. However, over several years of trying to obtain absolute photometry of isolated stars, we have found that the limiting accuracy of JHK measurements is only about 3%. To achieve even 3% takes much effort. It is not the detector or the terrestial atmosphere that limits the accuracy of these measurements, but instead the limits are due to a lack of definition of the natural system being used, and also due to the poor quality of some of the standard stars.

In the early days of infrared astronomy, 5% or even 10% photometry allowed one to do useful science, but it is important now that we achieve the potential 1% accuracy of modern day instruments. For example, in our work on cool dwarf stars this factor of three improvement would allow us to determine the metallicity of the atmospheres of such stars, and improve the determination of fundamental parameters such as temperature and luminosity by a similar factor.

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We have used observations of Elias *et al.* stars, made during several observing runs, to derive new colour transformations between the CIT J, H, K photometric system and systems currently in use at Cerro Tololo, Mauna Kea and Kitt Peak. The precision of the J, H, K data for some of the stars observed by Elias *et al.* is improved and the system extended to fainter stars suitable for use with larger telescopes and/or infrared arrays.

2. The Sample

The observing runs whose results are used here were: two runs at NASA's Infrared Telescope Facility on Mauna Kea in 1990 and 1991 using a single aperture detector; a run in February of 1992 on the 50-inch telescope at Kitt Peak using a single aperture detector; and a run on the 4-m telescope of the Cerro-Tololo Inter-American Observatory in April 1992 using an infrared array.

TABLE 1. NUMBER OF JHK OBSERVATIONS OF ELIAS *ET AL.* STARS

Name	J−K	IRTF 1990 PRIMO 1 3/30−4/2	IRTF 1991 PRIMO 1 2/15−2/17	CTIO 1992 IR IMAGER 4/24	KPNO 1992 OTTO 2/28−2/29	Total
HD 161743	0.005	0	0	1	0	1
HD 44612	0.020	0	0	0	2	2
HD 130163	0.020	2	0	5	0	7
HD 75223	0.045	2	0	1	0	3
HD 106965	0.060	4	13	0	6	23
HD 129653	0.060	0	0	0	1	1
HD 77281	0.075	4	1	1	2	8
HD 129655	0.125	11	3	0	0	14
HD 161903	0.150	5	0	1	2	8
Gl 105.5	0.715	0	2	0	2	4
Gl 299	0.740	9	8	1	1	19
Gl 748AB	0.770	0	0	0	1	1
Gl 347A	0.780	0	1	1	1	3
Gl 390	0.825	12	0	0	1	13
Gl 811.1	0.825	0	0	1	0	1
G 77-31	0.900	0	1	0	1	2
Gl 406	0.980	4	1	0	1	6
BD+0°1694	1.055	0	0	0	4	4

Table 1 lists the 18 Elias *et al.* stars used in this work, which range from A-type to M-type stars. We are preaching to the converted here, but of course to carry out accurate photometric measurements several standard stars must be observed each night, where the stars cover a range of colour and airmass. Such measurements take a good fraction of the available telescope time (at least 10%), and furthermore the major part of the data reduction involves using the standards to properly calibrate the data, and to determine the extinction and transformation coefficients. On average we made 12 standard star observations every night.

3. Colour Transformations

Table 2 gives the colour coefficients required to convert to the CIT system, determined by us using the observing runs described above. The coefficients listed are defined as follows:

$$J-H_{CIT} = A(J-H) + B$$
$$H-K_{CIT} = A(H-K) + B$$
$$J-K_{CIT} = A(J-K) + B$$
$$K_{CIT} - K = A(J-K)_{CIT} + B$$

In cases where no second coefficient value is given B=0. Transformations published by other authors for various systems are also given in Table 2.

TABLE 2. COEFFICIENTS FOR TRANSFORMATION TO CIT SYSTEM

System	Coefficients A, B for:			
	J−H	H−K	J−K	K
IRTF90[1]	0.923	1.047	0.960	−0.05
IRTF91[2]	0.88	1.13		
IRTF[3]	0.847	1.050		0
UKIRT[4]	0.920	0.960	0.936	−0.018
UKIRT[5]	0.929	0.893	0.908	0.05
CTIO[6]		0.94	0.88	0
CTIO[7]	1.00	0.94	1.00	0
ESO[8]			0.874	−0.01, 0.019
KPNO[9]	0.995	0.959	0.985	−0.023
HCO[10]	0.92	1.00		0
AAO[11]	0.876, 0.013	0.954	0.897	0, −0.014
Johnson/Glass/Carter/SAO[12]	0.89[±.03]	0.94[±.03]	0.91[±.01]	0, −0.01

1) This work, using PRIMO 1.
2) This work, using PRIMO 1. Less well defined than the 1990 transformation.
3) RC1 photometer, Humphreys *et al.* 1984, A.J. **89**, 1155.
4) UKT9 photometer, Casali & Krisciunas, 1991, private communication.
5) UKT9 photometer, Leggett & Hawkins 1988, M.N.R.A.S. **234**, 1065.
6) This work, using IR IMAGER.
7) Elias *et al.* 1982, A.J. **87**, 1029.
8) Bouchet *et al.* 1991, A & Ap. Suppl. Ser. **91**, 409.
9) This work, using OTTO.
10) Persson *et al.* 1977, A.J. **82**, 729.
11) Elias *et al.* 1983, A.J. **88**, 1027.
12) Bessell & Brett 1988, PASP **100**, 1134; Leggett 1992, Ap.J. Suppl.

The main points to notice in Table 2 are that the various 'natural' systems differ significantly from each other, and that there is now no commonly used system that looks like the old CIT system. Not correcting properly from the standard star system to that of the instrument used can lead to errors in the determined colours of 5–10% for red stars.

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Differences between systems can in most cases be easily understood, as observatories use different filters, especially for the J band. Moreover the edges of the JHK filters are often determined by the terrestrial atmosphere, and so the effective bandpass can differ from site to site. In some cases however the difference is not easily understood, for example the UKIRT and IRTF observatories on Mauna Kea use the same filter set at equivalent sites. Presumably in this case the colour term is due to some optical path difference, such as perhaps the gold-coated dichroic employed by UKIRT.

We are currently investigating the cause of time variations in the colour transformations, such as those demonstrated for the IRTF and UKIRT in Table 2. We are investigating how the transformation depends on when the mirror was resurfaced or cleaned. Some time dependence could perhaps also be caused by slowly changing atmospheric conditions which alter the effective filter bandpasses.

As the CIT system does not represent any system used today another system should be adopted as the 'standard'. However there is no overlap or agreement between the various systems commonly in use. Clearly a better defined filter set is required that avoids the edges of the terrestial windows, and this system would then be the obvious one to adopt. Milone *et al.* will be suggesting new infrared filter profiles later in this meeting.

4. New Standards

The 6th magnitude Elias *et al.* standard stars are too bright for use with the new infrared arrays on larger telescopes. Table 3 lists 14 stars that we suggest could be adopted as primary or secondary JHK standards. These stars are taken from compilations of published photometry for white dwarf and red dwarf stars by Leggett (1989, 1992) and also from a study of the South Galactic Pole area by Leggett & Hawkins (1988).

TABLE 3. FAINT PRIMARY OR SECONDARY STANDARD STARS

Name	Source[a]	RA 1950	Dec 1950	Proper "/yr	Motion θ	Opt.[b] mag.	J−H	H−K	K	No. Obs.
SGP 174	LH	00 47 55.9	−26 55 43			12.0R	0.83	0.23	7.92	25
SGP 157	LH	00 50 28.6	−27 22 18			19.6R	0.63	0.43	12.47	4
SGP 69	LH	00 59 41.2	−25 47 16			18.4R	0.58	0.30	12.67	4
SGP 50	LH	01 01 29.9	−26 36 03	0.302	165.0	12.0R	0.60	0.22	8.54	26
Hyad 214	LH	04 16 49.8	+16 38 12			19.9R	0.61	0.34	13.43	6
LHS 211	L92	05 45 14	+08 22 00	1.218	135.4	14.11	0.53	0.20	10.41	2
LHS 212	L89	05 53 47	+05 22 12	1.056	207.0	14.10	0.20	0.11	12.63	2
LHS 216	L92	06 11 07	+15 11 48	1.399	152.8	14.66	0.47	0.24	10.59	2
LHS 39*	L92	11 03 02	+43 46 42	4.531	281.9	14.40	0.52	0.29	7.85	3
LHS 2978	L92	14 44 23	−12 31 42	0.545	246.7	12.09	0.61	0.20	8.01	2
LHS 399	L92	15 33 08	+17 52 48	1.219	263.0	12.37	0.53	0.22	7.97	2
LHS 421*	L92	16 33 27	+57 15 06	1.620	316.0	12.91	0.47	0.28	7.79	2
LHS 429*	L92	16 52 55	−08 18 12	1.190	222.5	16.80	0.58	0.37	8.82	5
LHS 474*	L92	19 14 31	+05 04 48	1.461	203.1	17.50	0.66	0.44	8.80	4

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a) Sources are Leggett & Hawkins (1988), Leggett (1989), Leggett (1992)
b) Optical magnitude is V, or R from Leggett & Hawkins (1988) if so indicated
*LHS 39 is an emission line flare star
*LHS 421 is an emission line, optically variable, eclipsing binary
*LHS 429 is an emission line star and may be a flare star
*LHS 474 is an emission line flare star

All except two of the stars listed are red dwarfs. We believe that these stars are stable in the infrared, even if they vary in the optical. However we have found evidence of infrared variability in at least one red dwarf star, as discussed in the next section.

5. Infrared Variability and Problem Standards

We have found that one of the Elias *et al.* stars, Gl 105.5, varies from night to night by ~10% at J, H and K. The star appears hotter when it is fainter in the IR, and based on our photometry varies from a dK8 type to dK5. We have searched the literature (including a SIMBAD database search) and have not found any reference to this star flaring or being variable. The known flare star Gl 406 (Wolf 359) does not show any sign of infrared variability. Table 4 lists the JHK values observed by us for Gl 105.5 on four different nights, as well as the values given by Elias *et al*, which are based on 22 measurements.

TABLE 4. OBSERVATIONS OF GL 105.5

Date	J	J−H	H−K	Error
Elias *et al.* 1982	7.240	0.605	0.110	±.007
16 Feb 1991	7.237	0.539	0.075	±.025
17 Feb 1991	7.179	0.571	0.162	±.040
28 Feb 1992	7.398	0.641	0.049	±.020
29 Feb 1992	7.243	0.621	0.118	±.010

This variability poses a problem for those of us trying to establish infrared standards; however for those interested in variable stars this could be an exciting opportunity. The effect we have seen may be an example of a 'negative infrared flare' as described by Gurzadyan (1988). He suggests that such flares would occur simultaneously with a positive optical flare, in the case of flares due to fast electrons appearing in the outer regions of a star.

Besides Gl 105.5, we have found problems at the ≥3% level for two other Elias *et al.* stars. Our revised values for these two stars, Gl 390 and BD+0°1694, are given in Table 5. Our estimated uncertainties and those quoted by Elias *et al.* are given in the Table. Elias *et al.* made many more observations of BD+0°1694 than we did; this red giant may be another infrared variable.

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TABLE 5. REVISION OF ELIAS *ET AL.* VALUES

Name	Elias *et al.*					This Work				
	K	J−K	H−K	No. Obs.	Error, mag.	K	J−K	H−K	No.	Error, mag.
Gl 390	6.045	0.825	0.205	11	0.007	6.085	0.769	0.196	13	0.020
BD +0°1694	4.585	1.055	0.225	27	0.005	4.620	1.027	0.219	4	0.015

6. Conclusions

We have found that about 20% of the commonly used Elias *et al.* (1982) standard stars display errors of ≥0.03 magnitudes. New and fainter standards are needed for use with infrared arrays on the larger telescopes. Such work is in progress at the major observatories; for example Casali *et al.* at UKIRT and Elias *et al.* at CTIO have started observing Landolt standards to define equatorial infrared standard stars. In this paper we have presented 14 additional infrared-faint stars that could be adopted as standards.

A new standard system, with better defined JHK filter bandpasses, is required before the full potential of modern day detectors can be routinely achieved. Such a filter set will be described by Milone *et al.* later in these proceedings.

Finally, we make a plea to the major observatories that they monitor their users' data reductions, recording not only for example changes in instrumental zero point and atmospheric extinction, but also to make note of any standard stars that deviate from the adopted calibration. The problems we had with some of the 10-year-old Elias *et al.* stars should have been made public before now.

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Discussion

E.F. Milone: *You haven't talked about extinction corrections. Could the difference between your ITF and UKIRT results be due to different H_2O content, from night to night, for the two sets of observations?*

Leggett: No we are happy with our extinction measurements. The difference appears to be in the telescope or instrument optical path.

R.R. Shobbrook: *If the J, H and K band-passes are defined by the atmosphere, they must also change with air mass. Is this a main part of the problem?*

Leggett: We try to observe at high airmasses. Although the terrestrial atmospheric windows are narrow, and do affect the filter cut-offs, I don't think airmass effects are the main part of the transformation problem.

M. Cohen: *Now that we have these absolutely calibrated Sirius and Vega IR spectra, they are available as a resource for anyone wishing to calibrate their own IR filters, new or old. If they can send us (digitally) their filter transmission profile at its cryogenic operating point, we can provide the 'zero magnitude flux calibrations' by integrating over our calibrated Vega spectrum.*

I.S. Glass: *I think your estimate of errors is unduly pessimistic, especially amongst southern hemisphere observations. We have found rms differences with Elias at the 0.01 magnitude level, at H K at least, and a little worse at J.*

Leggett: The northern hemisphere systems are perhaps not as well defined as the southern ones. Also you do have to be careful which Elias standards are used.