STELLAR EFFECTIVE TEMPERATURES THROUGH THE INFRARED FLUX METHOD

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Abstract.
    The principle of the method and its advantages are recalled, as well as the works giving such T_{eff}. Although the method is almost model independent, the monochromatic red fluxes play an important part. The resulting T_{eff} depends on the blanketing in the models. The stellar metallicity and gravity have to be known to avoid uncertainties of about 1%. In principle an accuracy around 1% on T_{eff} could be obtained, but the uncertainty on the absolute red flux calibration, due to the unsolved problem of the Vega red flux, prevents this from being achieved.

1. Introduction and principle of the method

More and more accurate stellar effective temperatures are required, either for atmosphere modelling or to study the internal structure, to better scale the HR diagram, specially in connection with the high accuracy of Hipparcos parallaxes, and so to fix better the evolutionary track for a star. Then we ask: what accuracy is achievable on T_{eff}, is it possible to obtain effective temperatures within 1% or better, as asked for and claimed in some works? Why the infrared flux method (IRFM)?
    The most direct method to derive T_{eff} relies on the Stefan law. It requires the stellar angular diameter θ and the total flux received from the star, integrated over the whole wavelength range f. Indeed :

$$F = \sigma T^4 \qquad \text{and} \qquad \theta = 2R/d \qquad \text{so that} \qquad f/F = \theta^2/4 \quad (1)$$

where R is the stellar radius and d the stellar distance.
    However the angular diameter is known for the brightest stars only and it has a poor accuracy compared to the aim of T_{eff} within 1%. As reported

by Davis (these Proceedings), for a magnitude 3 star the uncertainty is at least 5%, leading to 2.5% on T_{eff}.

In their method, Blackwell and Shallis (1977, 1980) assume that in the infrared spectrum, the relation (1) holds also for monochromatic wavelengths :

$$f_\lambda/F_\lambda = \theta^2/4 \quad (2) \qquad R = F/F_\lambda = \sigma T^4/F_\lambda = f/f_\lambda = R_{obs} \quad (3)$$

so that the ratio of (1) over (2) leads to (3) where the angular diameter enters no more. The ratio R_{obs} deduced from the observations is compared to the ratio R computed from the atmosphere models. Blackwell et al. justify their assumption by several arguments: the small sensitivity of the infra-red flux to T_{eff}, the smaller blanketing in the infrared, the more certain stellar opacity sources.

First we list the existing works on the IRFM, then we discuss in turn the required observations and models, and the uncertainties they induce on T_{eff}.

2. Stars with effective temperatures through the IRFM

The groups who derived T_{eff} through the IRFM are listed in Table 1 for the normal stars, with the type of the stars and their number. Table 2 lists the works on Ap and Am stars.

3. Influence of the models and of the stellar metallicity and gravity

In the works earlier than 1990, it was assumed that the ratio F/F_λ, where F is given directly by the Stefan law and F_λ by atmosphere models, does not contribute to the uncertainty on T_{eff}. Mégessier (1994) showed qualitatively and quantitatively that, in fact, the model itself has an influence on T_{eff} derived from a given observed ratio R_{obs}. That is logically explained by the increase of blanketing in the more recent codes. The numerous UV spectral lines absorb flux that is redistributed in the Paschen continuum, which is then enhanced. The near infrared monochromatic fluxes being larger from the more recent codes, the resulting $R = F/F_\lambda$ will be smaller. The relation R vs T_{eff} is lowered and then it leads to larger T_{eff} for a given R_{obs}. This is illustrated in Table 3, which compares, for few stars, IRFM T_{eff} obtained from the same R_{obs} and from R (T_{eff}) for different models. The change in T_{eff} is larger than 1% between the oldest codes considered and ATLAS9, and it can be as large as 350K, i.e., 2.4%.

Mégessier (1994) showed that the relations R (T_{eff}) computed for different metallicities and gravities differ, so that using a relation with inappropriate [M/H] or log g for a star will induce systematic errors in T_{eff}. This

TABLE 1. Stars T_{eff} from the IRFM

Authors	N	Type	Class
Blackwell and Shallis (1977)	7	A0 to F8	V, III, II, I
Blackwell et al. (1980)	28	A, F, G	V, IV, III
Saxner et al. 1985	31	F, G	V, IV, III
Leggett et al. (1986)	22	O to M	V, IV, III
Mégessier (1988)	9	B3 to A2	V, IV, III
Blackwell et al. (1990)	114	F to M	V, IV, III
Blackwell et al. (1994)	114	F to M	V, IV, III
Alonso et al. (1994)	31	B to M	V, IV, III, II
Alonso et al. (1996)	475	F to M	V, IV

TABLE 2. Stars T_{eff} from the IRFM for Ap, Am stars

Ap stars	N	Am stars	N
Shallis and Blackwell (1979)	6	Lane and Lester 1984	10
Lanz (1984)	12	Mégessier et al. (1990)	1
Mégessier (1988)	12	Mégessier et al. (1993)	2
		Smalley (1993)	25

is illustrated in Table 4 for few stars. The influence of [M/H] is larger than that of log g. It is effective in the same way as the more or less blanketed models. The error on T_{eff} is around 1% and it depends on T_{eff}.

TABLE 3. IRFM T_{eff} from different models

		$T_{a,b}$	T_{atlas8}	T_{atlas9}	ΔCG-9	%	Δ9-8	%
β Sex	B6V	14505 [a]	14746	14860	355	2.4	114	0.80
α Leo	B7V	12025 [a]	12075	12145	120	1.0	70	0.58
γ Lyr	B9III	9950 [a]	10062	10102	152	1.5	40	0.40
α CMa	A1V	9750 [a]	9870	9900	150	1.5	30	0.30
μ And	A5V		8000	7985			-15	-0.18
α Oph	A5III		7890	7882			-0.8	-0.10
45 Boo	F5V	6663 [b]	6720	6765	102	1.52	45	0.67
π Peg	F5III	6170 [b]	6220	6280	110	1.77	60	0.96

[a] T_{eff} from Carbon and Gingerich (1969) models
[b] T_{eff} from old MARC models (Gustafsson et al. 1975)

TABLE 4. Influence of the model metallicity and gravity on IRFM T_{eff} for 8 bright stars

$\longleftarrow$			[M/H]			$\longrightarrow$	$\longleftarrow$	log g	$\longrightarrow$
	0.0	0.3	0.5	$\Delta_{.0}^{.3}$	$\Delta_{.0}^{.5}$	%	0.4	0.3	$\Delta_{.4}^{.3}$
β Sex	14860	14957	15037	97	177	1.18	14860	14905	45
α Leo	12145	12207	12260	62	115	0.94	12145	12187	42
γ Lyr	10102	10139	10172	37	72	0.72	10102	10080	-22
α CMa	9900	9940	9967	40	67	0.67	9900	9875	-25
μ And	7985	8028	8057	43	72	0.90	7985	7911	-74
α Oph	7882	7930	7957	48	75	0.95	7882	7828	-54
45 Boo	6845	6900	6935	55	90	1.30	6845	6845	0
π Peg	6280	6336	6378	56	98	1.55	6280	6280	0

4. The required observations and and their accuracy

The total integrated flux received at the earth f is obtained from the flux distribution, calibrated in the visible at $\lambda5556$ Å by f_{5556}^{*} given in Eq. 4

$$f_{5556}^{*} = f_{5556}^{Vega} 10^{-0.4(V_* - V_{Vega})} \quad (4) \qquad f_\lambda = C_\lambda 10^{-0.4 m_\lambda} \quad (5)$$

where $f_{5556}^{Vega} = 3.46 \ 10^{-11} \mathrm{Wm}^{-2}\mathrm{nm}^{-1}$ is the reference visual flux calibration (Mégessier 1995) as recalled in my previous talk. The construction of the energy distribution has been presented by Bless (this proceedings). The observed red monochromatic flux is given by Eq. 5, where C_λ is the near infrared flux calibration at the wavelength λ.

The uncertainty on f, which is mainly due to the spectrophotometry accuracy, is different in the three wavelength ranges: UV, visible and red. As a whole, it is generally less than 1% for the brightest stars. (see Mégessier 1997 for a complete discussion of IRFM Teff accuracy). The uncertainty on f_{5556}^{Vega} is 0.7% as given in Mégessier (1995). The visual magnitudes V can be measured to better than 0.01mag. The problem of the accuracy on the red calibration C_λ has been discussed earlier (Mégessier in this proceedings). If one excludes the problem of the difference between Vega observed flux and model's, C_λ is known within about 2% or 3% and the red magnitudes are measured to 0.02 magnitudes or better. Combining all these uncertainties leads to a relative error on T_{eff} less than or equal to 1%. Thus the aim of an accuracy better than 1% seems to be achieved.

But the values given here are valid for well observed bright stars, specially with good spectrophotometry. Moreover, the error due to the problem of the red calibration has to be added i.e. 2% or more, depending on the

red monochromatic wavelength, and if the metallicity and gravity of the star are not certain, one more error has to be taken into account, which can be around 1% or more.

5. Conclusion

The infrared flux method is the closest to the Teff definition, it relies almost not on atmosphere models. Then it should give Teff on an absolute scale. The IRFM Teff accuracy can be as good as 1%, may be somewhat better. Then the method is very attractive.

However several limitations exist. The energy distribution is not available for a large amount of stars, and its measurement is not as easy as that of photometric colours. If it is derived from photometric indices or models, the accuracy is lowered. The method is not totally independent of the models and one should be really confident in the model red fluxes. If the visible flux calibration is well constrained, it is not the case of the red ones and the additional error induced is likely the largest among those mentioned here. Also, the metallicity and the gravity of the stars have to be known.

Then we can retain the advantages of the infrared flux method, but also remember its present limitations. It would provide Teff of stars bright enough, used themselves as references. The problem of the red flux calibration is the most important to solve in oder to get an accuracy around 1% on Teff.

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