4. STELLAR FLUX DISTRIBUTIONS

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THE VISUAL AND INFRARED FLUX CALIBRATIONS

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Abstract. We present a critical review of the available visible and near infrared flux calibrations. In the visible, the accuracy and the good consistency of three independent determinations of Vega monochromatic flux allow one to recommend with confidence $f_{5556-Vega} = 3.46\ 10^{-11} Wm^{-2} nm^{-1}$ within 0.7%. In the near infrared, the possible flux excess of Vega, as compared to that derived from the atmosphere models fitting the visible, does not allow such a good accuracy. The agreement between the calibrations, either from a comparison of Vega to blackbodies or from solar analog stars, would question the calibrations relying on models. More work is necessary to conclude with confidence and then to reduce the uncertainty on the near infrared calibrations.

1. Introduction

Significant progress is made possible in our knowledge of the fundamental stellar properties because of the recent improvements both in the models (atmospheres, internal structure, evolution) and in the accuracy of the direct measurements (Hipparcos, IRAS, Hubble, photometry and spectrophotometry). Then it is important to constrain the accuracy of the absolute stellar fluxes required for comparison to the models and for the stellar parameter determinations, *which depends strongly on the absolute astrophysical flux calibrations.* In this review, I shall present successively:

- The principle of measurement of the absolute astrophysical fluxes.
- The calibrations available in the visible, which rely mostly on Vega.
- The calibrations available in the near infrared, which rely on Vega and on solar analog stars.
- A discussion on the calibration relying on model atmospheres.

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– A conclusive discussion on the present limitations, and what is necessary to improve the calibrations.

2. Principle of the absolute astrophysical flux measurements

The two methods relying on observations that have been used are presented.

2.1. DIRECT COMPARISON OF THE STELLAR FLUX TO A REFERENCE SOURCE

The stellar flux and the standard source, placed in the vicinity of the observatory, are observed with the same telescope, equipped with the same receptor and photometric filter. The resulting accuracy depends on two important factors:

– the intrinsic quality of the standard sources and their own calibrations
– the atmospheric transmission and the correction for the atmospheric extinction.

The reference sources used are Cu or Pt blackbodies, Tu lamps or standard furnaces. They have to be calibrated in laboratory against gold blackbodies. Indeed the gold melting temperature, T = 1337.58 K, is the highest on the International Practical Temperature Scale, but the Au blackbodies can be operated in laboratory only. Moreover, it is preferable to work with a source which temperature is as high as possible, to be compared to stars which are far hotter than the blackbodies. The melting temperature of Cu is T = 1357.8 K and that of Pt is T = 2042.1 K. The Tu strip lamps can be worked at higher temperatures, up to 2900K, however they are less reliable since their emissivity depends strongly on the intensity of the current and on their temperature. The intensity radiated by each source, which is given by the Planck law, is accordingly a function of the wavelength. The emission of Tu lamps and Pt-BB are strong enough from λ=3000 to 9000 Å, whereas the Cu-BB emission is faint shorter than 6000 Å. (for more details see Mégessier 1995 and references therein)

2.2. CALIBRATION FROM THE SOLAR ABSOLUTE FLUX THROUGH ANALOG STARS

This method has been used in the near infrared domain. The energy distributions of the solar analog stars are supposed to be identical to that of the sun, so that they have the same color indices as it, in the Johnson photometric system (V, J, H, K, L, M). The solar energy distribution is known (Neckel and Labs 1981). The solar flux density in each photometric band $I_{V_\odot}$, $I_{J_\odot}$,..., is computed by convolving the solar energy distribution with the filter transmission functions. These solar fluxes are raccorded to the stellar's by means of Vega, for which the flux density trough the filters are obtained by the convolution of Vega flux models, calibrated according to the monochromatic flux $f_{5556-\mathrm{Vega}}$, with the filters transmission functions.

Then, in each band, the solar flux density is scaled in proportion to the differences $(V_\star - V_\odot)$, ..., i.e.: $I_{V\star} = I_{V\odot}\ 10^{-0.4(V_\star - V_\odot)}$, ..., and the absolute flux for a null magnitude is given by $I_{m=0.0} = I_{m\star}\ 10^{-0.4\ m\star}$, where $m_\star$ is the stellar magnitude in the color considered.

3. The visible flux calibration

From the beginning, the A0V star Vega has been chosen as the reference standard star in photometry as well as for the absolute flux measurements. The absolute visual calibrations are given as its monochromatic flux at λ 5556 Å. The improvement of the techniques allowed an increase of the accuracy. We discuss the calibrations obtained by various groups since that performed at Palomar 5m telescope by Oke and Schild (1970). Table 1 gives, for each group, the value of f_{5556} for Vega, the reference sources and the observatory where they worked.

TABLE 1. Visible flux calibrations f_{5556} for Vega

Authors	f_{5556} x 10^{-11} $Wm^{-2}nm^{-1}$	sources	Observatory
Oke and Schild (1970)	3.36 ± 2%	Tu, Cu	Palomar
Hayes et al. (1975)	3.45 ± 1.9%	Tu, Cu	Lick, Mt Hopkins
Tüg et al. (1977)	3.47 ± 1%	Cu, Pt	Lowell
Terez (1985)	3.44 ± 1.2%	Tu	Mt Ararat, Armenia

An extensive discussion of the accuracy of the visual calibration is given in Mégessier (1995). The main points are reported here.

In the visible domain, the correction for the extinction due to earth atmosphere is constrained satisfactorily and it contributes for less than 0.5% to the calibration uncertainty (see by ex. Hayes and Latham 1975).

The role of the standard reference source is crucial and the blackbodies are more reliable than the Tu lamps, as mentioned above. The calibration against the Au blackbody is important, as well as an inter-comparison of the Au blackbodies developed in the various laboratories over the world.

One has to remark the progressive improvement of the intrinsic accuracy obtained on each calibration (Table 1). Clearly, the Palomar calibration is lower than the three others for which the internal consistency is as good as ± 0.4%. Mégessier (1995) showed that the low Palomar value is due to the

Tu lamp worked by Oke and Schild (1970). Indeed the comparison of the Tu lamps performed by Hayes, Oke and Schild (1970) shows a systematic difference in the emissivities, that of the Palomar lamp being the largest. This leads to an underestimation of the stellar flux at Palomar. Then the best absolute Vega flux is given by the mean of the values obtained by the three latest groups listed in Table 1, weighted by the uncertainties.

The most reliable visible calibration is:

$\mathbf{f_{5556-Vega} = 3.46\ 10^{-11} Wm^{-2} nm^{-1}}$ **with** $\sigma = \mathbf{0.025}$**, i.e. 0.7%**

One has to notice that the mean values of $f_{5556-Vega}$ given successively by Hayes and Latham (1975) and Hayes (1985), widely used up to recently, were lowered by the Palomar value.

4. Near infrared flux calibrations

Three methods have been used, if one excepts that relying on the assumption that the stellar flux is given by the Planck law.

- The direct comparison of the observed Vega stellar flux to that of blackbodies or standard furnaces, as in the visible. This has been done by Blackwell's group between 1980 and 1989 (Blackwell et al. (1983), Selby et al. (1983), Mountain et al. (1985), Petford et al. (1985), Booth et al. (1989))
- Photometry of solar analog stars calibrated through the solar absolute flux. Two works have been done by Wamsteker (1981) and Campins et al. (1985) respectively, the photometric data given by Wamsteker being included in Campins (1985) work. The principle of the procedure is recalled above in sect. 2.
- The comparison of Vega near infrared photometry to the atmosphere model energy distribution fitting the visible data. The most recent works are those of Bessell and Brett (1988), Blackwell et al. (1994), Alonso et al. (1994).

The comparison of the calibrations obtained through the three procedures shows that a systematic difference exists. The calibrations from Vega flux models are lower than those derived either from direct comparison to furnaces or through the solar analog stars.

4.1. CALIBRATIONS RELYING ON MODEL ATMOSPHERES - QUESTION OF THE VEGA NEAR INFRARED EXCESS

The discrepancy between the observed Vega near infrared flux and the models has been reported in several works: Campins (1985), Blackwell et al. (1983) and Mountains et al. (1985), who compared their absolute fluxes to Dreiling and Bell (1980) models, and recently Castelli and Kurucz (1993), comparing ATLAS9 Vega energy distribution to the observed one constructed by Hayes (1985). The discrepancy increases with the wavelength, from 1 or 2 % at 1.25 μm to 4% at 2.2 μm and more than 6% around 3.7 μm (Blackwell et al. 1983 and Mountains et al. 1985). This is of importance since, if the star presents a near infrared excess, logically the calibrations from models yield lower calibrations (fluxes for a null magnitude) than the direct comparison to a blackbody. Indeed, one assumes the model, which has a lower flux than the star, represents the actual stellar flux. To be confident in the validity and in the accuracy of the calibrations, it is important to confirm whether Vega presents or not a flux excess as compared to the models.

The agreement between two independent works, by two different procedures relying on observations (Vega or solar analogs i.e. the first and second ones mentioned above) questions the third procedure relying on models.

If Vega near infrared flux is really larger than that of the models, one has to check the incidence on the works using absolute fluxes derived from model calibrations, specially the calibrations of new astrophysical measurements. Underestimated fluxes will be derived from such calibrations.

This effect is not an uncertainty but a systematic effect which has to be included in the uncertainty on the derived fluxes until this point is not cleared up. A more detailed study of that question will be given in Mégessier (1997).

5. Conclusion - Discussion - Requirements

In the visible, the values of the Vega monochromatic flux at λ5556 Å obtained totally independently by three groups using different absolute reference sources in different observatories are in excellent agreement. Then one can be confident and conclude that now the astrophysical visible flux calibration is satisfactorily determined. It is given by:

$f_{5556-Vega} = 3.46\ 10^{-11} Wm^{-2} nm^{-1}$ with $\sigma = 0.025$, i.e. 0.7%

In the near infrared domain the only series of direct absolute flux measurements agrees with that obtained from solar analog star measurements, but disagrees significantly from that obtained assuming Vega's energy distribution is given by atmosphere models. Then to choose between them and so increase the accuracy one has to answer the questions:

- Do the models represent actually Vega's energy distribution?
- Is Vega's energy distribution similar to that of the A0 V stars?
- Does Vega exhibit any flux excess in the near infrared?

What is required to go further?

- More absolute flux measurements in the infrared
- Observations of another A0V star?
- Improvements of the models?

- "Definitive" absolute solar energy distribution?
- Comparison of the standard reference sources to laboratory Au-blackbodies and an inter-comparison of the Au-BB from the different laboratories.

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DISCUSSION

PIERRE MAXTED: Has any attempt been made to model the IR excess of Vega in the 1-4 μm region?

CLAUDE MEGESSIER: Attempts exist to find an explanation for the near-IR excess of Vega. At wavelengths longer than 10 μm, it can be accounted for. In the near-IR, 1 to 5 μm, no explanation has been found and then it is not possible to model it.