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# Effective temperature determinations using the Infrared Flux Method

D. Dubaj[1] and R. Monier[2]

[1] Observatoire de Strasbourg, 11 rue de l'université, F-67000 Strasbourg, France
[2] Université de Montpellier, F-34000 Montpellier, France

**Abstract.** The spectral energy distributions (SEDs) from the ultraviolet to the infrared have been constructed for 41 main sequence A and F stars for which ultraviolet, optical spectrophotometry and infrared photometry are available. Their effective temperatures were derived using the infrared flux method (IRFM). Finally, the constructed SEDs have been compared to the predictions of ATLAS12 for the derived IRFM effective temperatures, adequate surface gravities and chemical composition when available to test the ability of models to reproduce the SEDs.

**Key words.** Stars: angular diameter – Stars: effective temperature – Stars: infrared flux method – Stars : spectral energy distribution

## 1. Introduction

The knowledge of the effective temperature is important because it is a basic parameter of a star used for the computation of the atmospheric model. We use the Infrared Flux Method (IRFM) (Blackwell et al. 1979) to derive effective temperatures for several field A and F stars which have multiwavelength data. For a given star, this method requires the construction of the observed spectral energy distribution from ultraviolet to infrared. It is thus a demanding method and can be applied so far only to a few bright field stars. The infrared flux method allows one to determine the effective temperature but also the angular diameter at various wavelengths in the infrared. We have used the derived IRFM temperatures to calculate theoretical spectral energy distributions using ATLAS9 (Kurucz 1991) and ATLAS12 (Kurucz 1993) in order to check the ability of model atmospheres to reproduce the observed spectral energy distributions. The effective temperatures of A and F stars can also be derived from the Balmer lines (see, e.g., Adelman et al. 2002).

*Send offprint requests to*: D. Dubaj, e-mail: dubaj@astro.u-strasbg.fr

## 2. Spectral energy distribution

To construct the observed spectral energy distributions, we used data from three wavelength ranges. For the ultraviolet range, data come from the IUE ( International Ultraviolet Explorer ) database (http://ines.vilspa.esa.es/iue/iue.html, Wamsteker et al. 1999). For the visible range, data came from two sources : Breger (1976) and Adelman et al. (1989). The infrared photometry was retrieved from various authors : Aumann, & Probst (1991); Baruch et al.

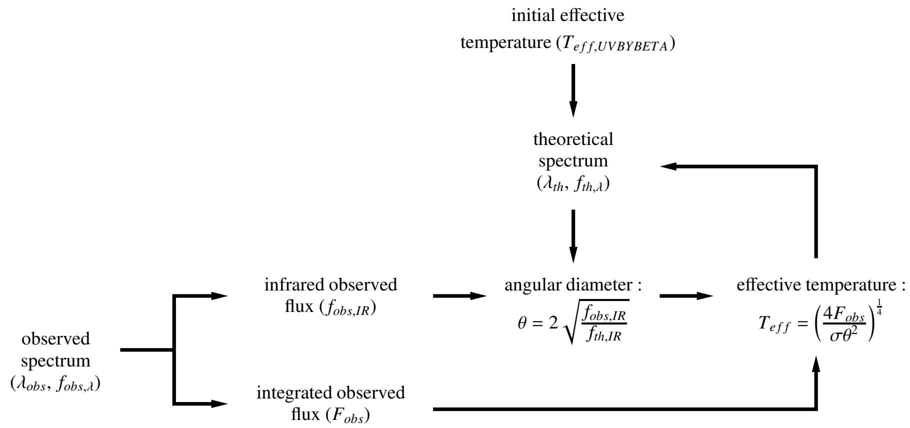



**Fig. 1.** The infrared flux method.

**Table 1.** Selected stars

| spectral type | Adelman data | Breger data |
|---|---|---|
| $A0IV-V$ | 4 | 6 |
| $A1IV-V$ | 2 | 3 |
| $A2IV-V$ | 1 | 5 |
| $A3IV-V$ | 2 | 6 ( +1 $A3III$ ) |
| $A4IV-V$ | 0 | 1 |
| $A5IV-V$ | 2 | 4 ( +1 $A5III$ ) |
| $A6IV-V$ | 0 | 0 |
| $A7IV-V$ | 3 | 8 ( +1 $A3III$ ) |
| $A8IV-V$ | 0 | 0 |
| $A9IV-V$ | 0 | 1 |
| $F0IV-V$ | 1 | 2 |
| Total | 15 | 39 |

(1983); Blackwell et al. (1979, 1990); Bonsack & Dyck (1983); Bouchet et al. (1991); Carney (1982); Carter (1990); Cohen et al. (1992); Gehrz et al. (1974); Guetter (1977, 1979); Johnson et al. (1966, 1968); Leggett et al. (1986); Selby et al. (1988); Van der Bliek et al. (1983) and Wamsteker (1981).

## 3. Selected stars

We have retained 15 stars which have photometry coming from Adelman et al. (1989) and 39 which have photometry secured by Breger (1976). Our sample covers the spectral type from A0 to F0 (see table 1). Thirteen stars are common to the two sets of data.

## 4. The Infrared Flux Method

### 4.1. Description

In order to apply the IRFM, it is necessary to construct the Spectral Energy Distribution (SED) from the ultraviolet to the infrared. The IRFM method and the used equations are summarized in Fig. 1. The angular diameter ($\theta$) is derived from the measured infrared fluxes and flux predictions using ATLAS9 or ATLAS12 at these wavelengths. The effective temperature ($T_{eff}$) can then be computed from the integrated observed flux ($F_{obs}$) and the angular diameter. The IRFM is an iterative procedure: from a first guess of the effective temperature, the angular diameter is deduced and used to derive an improved effective temperature. This refined effective temperature serves then to compute an atmospheric model which yields the predicted infrared flux used for a new computation of the angular diameter.

### 4.2. Initial effective temperature

To determine the initial effective temperature, we use the code UVBYBETA (Napiwotzki et al. 1993) which is a correction of Moon's code (Moon & Dworetsky 1985). This code needs

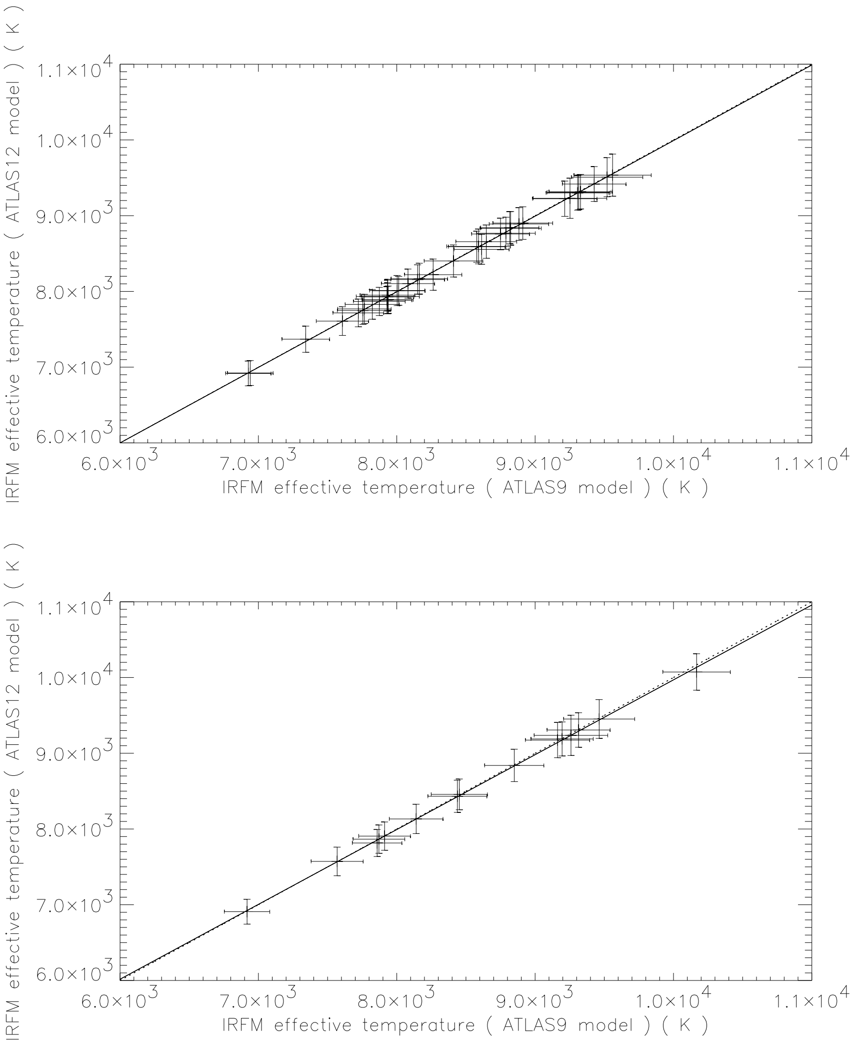



**Fig. 2.** Comparison between the effective temperature from IRFM using ATLAS9 and ATLAS12 for Breger's data (Breger 1976) (top) and for Adelman's data (Adelman et al. 1989) (bottom).

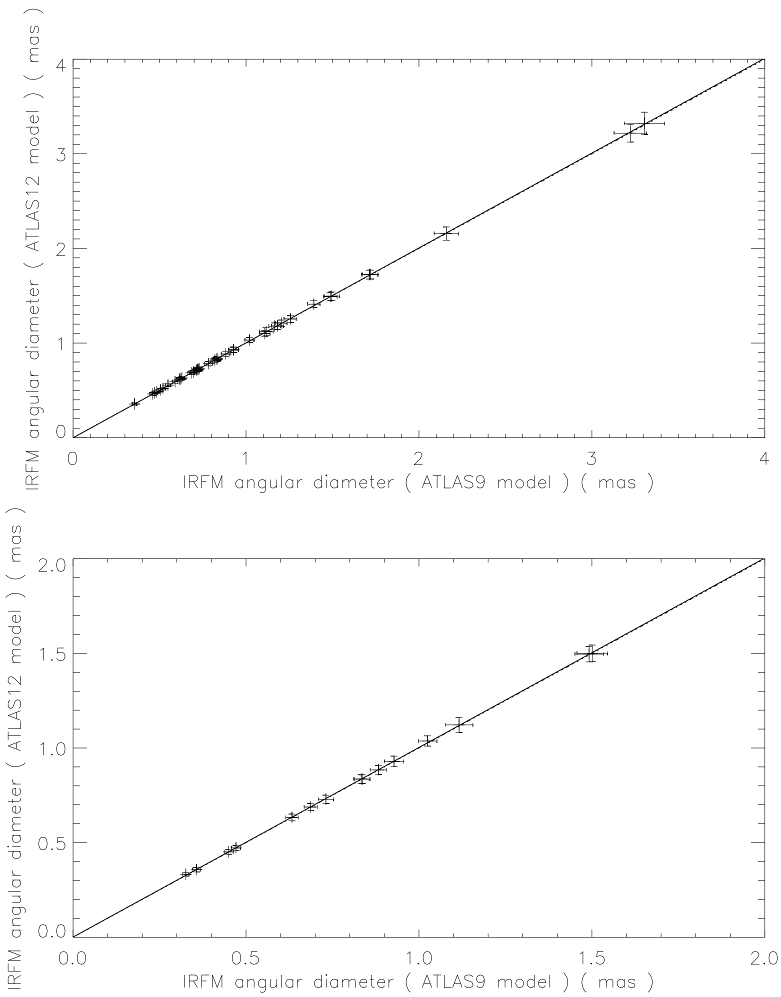



**Fig. 3.** Comparison between the angular diameter (bottom) from IRFM using ATLAS9 and ATLAS12 for Breger's data (Breger 1976) (top) and for Adelman's data (Adelman et al. 1989) (bottom).

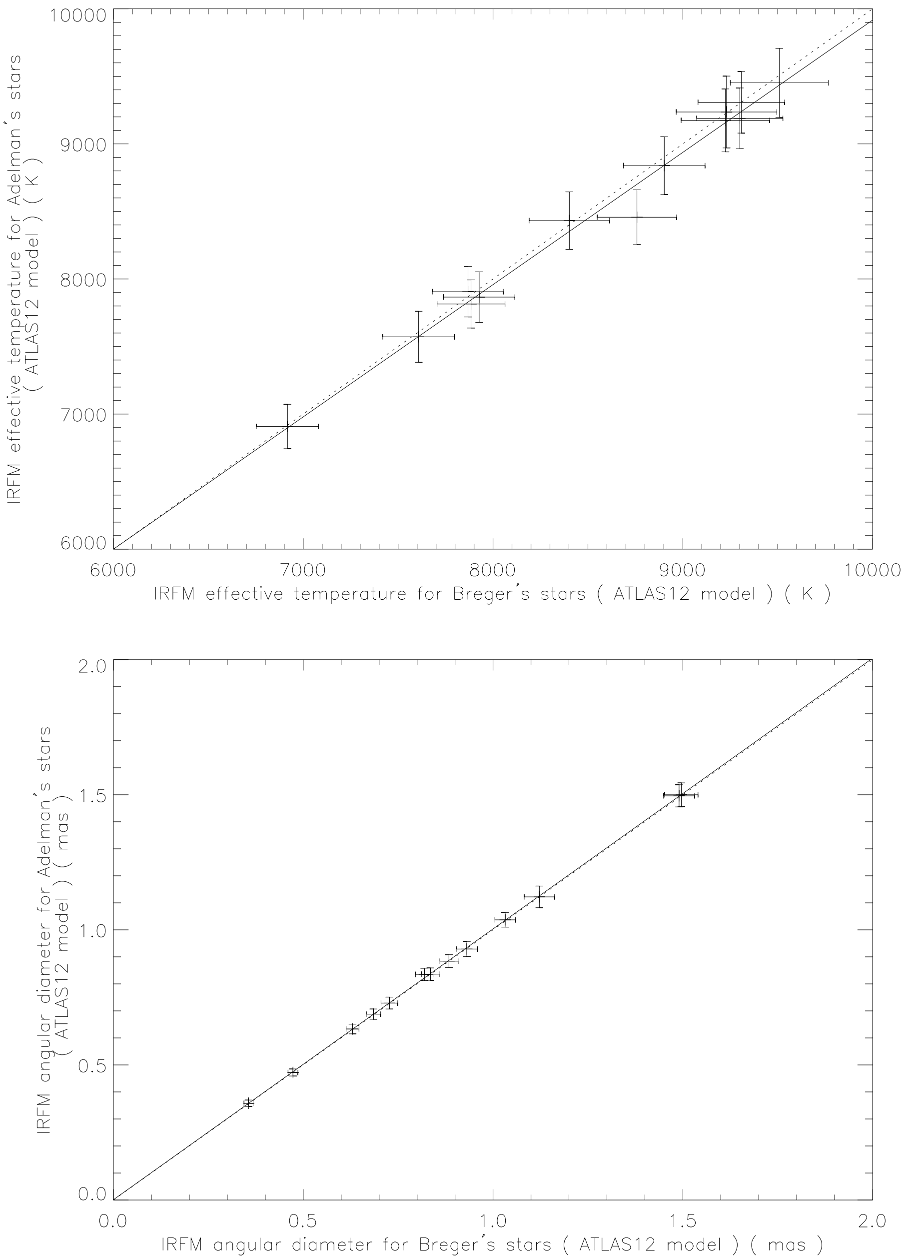



**Fig. 4.** Comparison between Breger's data (Breger 1976) and Adelman's data (Adelman et al. 1989) for the effective temperature (top) and for the angular diameter (bottom) derived from IRFM using ATLAS12.

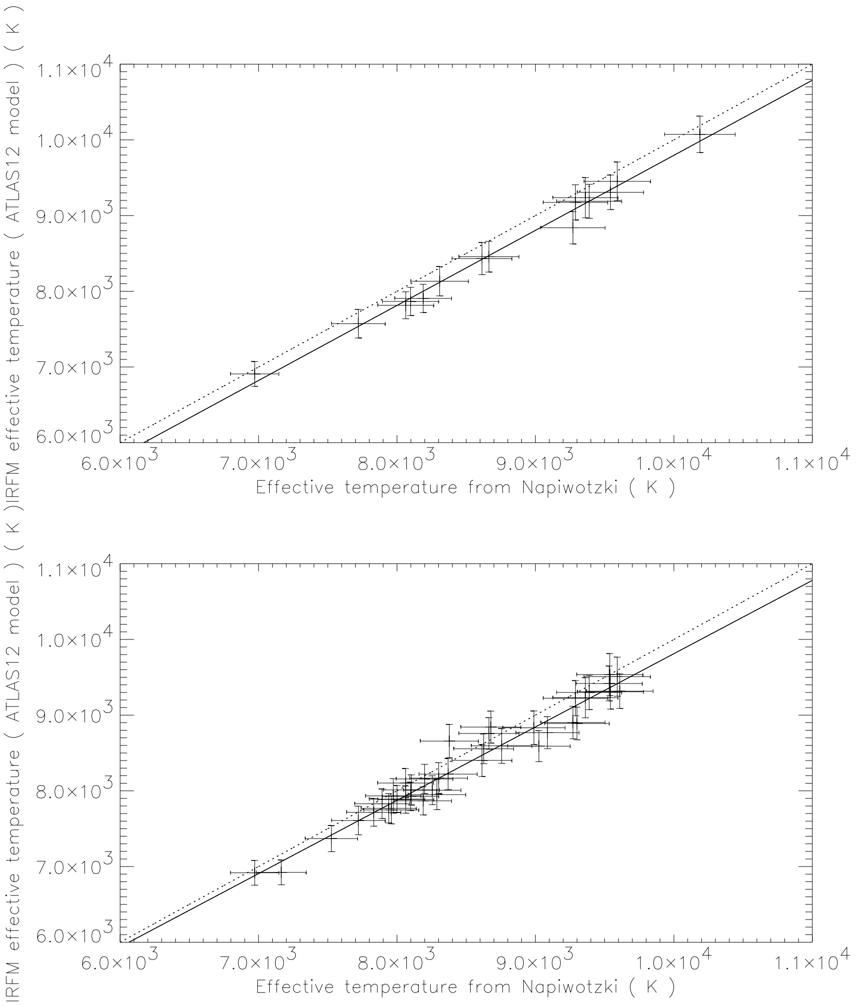



**Fig. 5.** Comparison between the effective temperature from UVBYBETA and IRFM using ATLAS12 for Breger's data (Breger 1976) (top) and for Adelman's data (Adelman et al. 1989) (bottom).

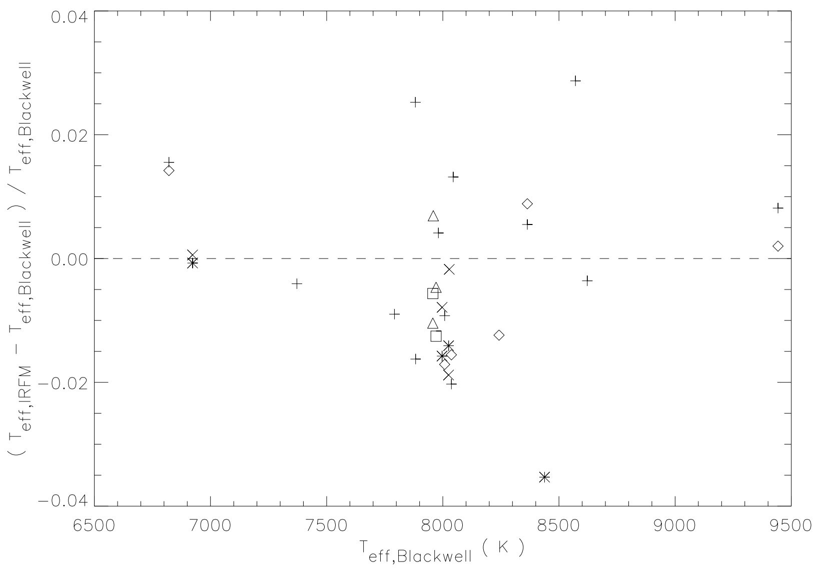



**Fig. 6.** Relative difference between our study and (Blackwell & Lynas-Gray 1998) (Breger : +; Adelman : diamond), (Blackwell & Lynas-Gray 1994) (Breger : triangle; Adelman : square), (Blackwell et al. 1990) (Breger : cross; Adelman : asterisk ).

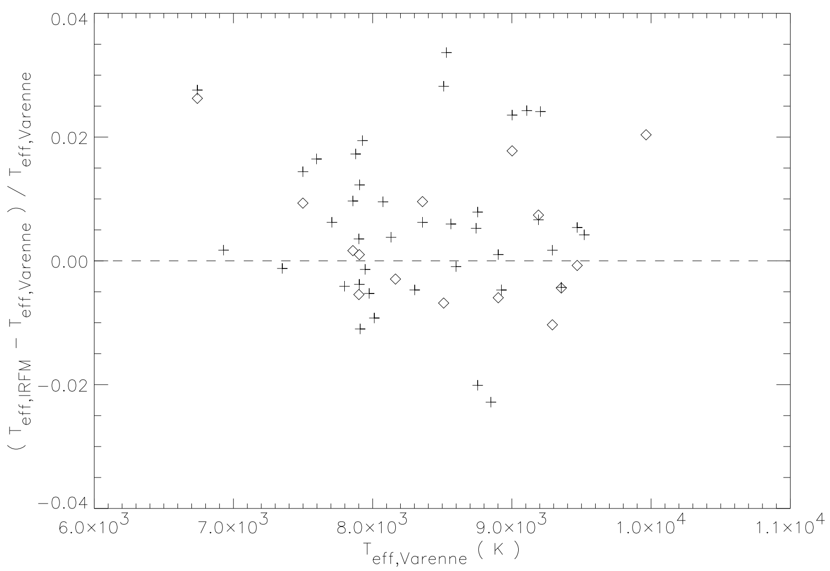



**Fig. 7.** Relative difference between our study and (Varenne 1999) (Breger : +; Adelman : diamond).

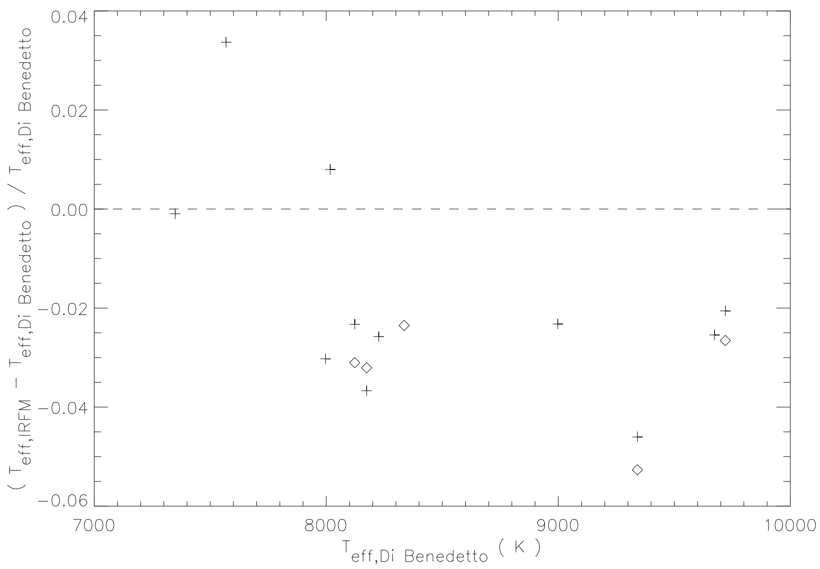



**Fig. 8.** Relative difference between our study and (Di Benedetto 1998) (Breger : +; Adelman : diamond).

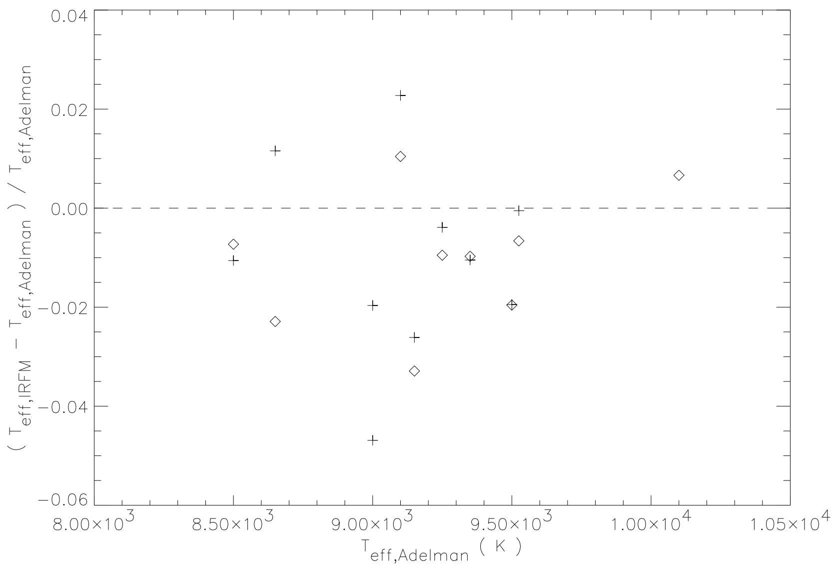
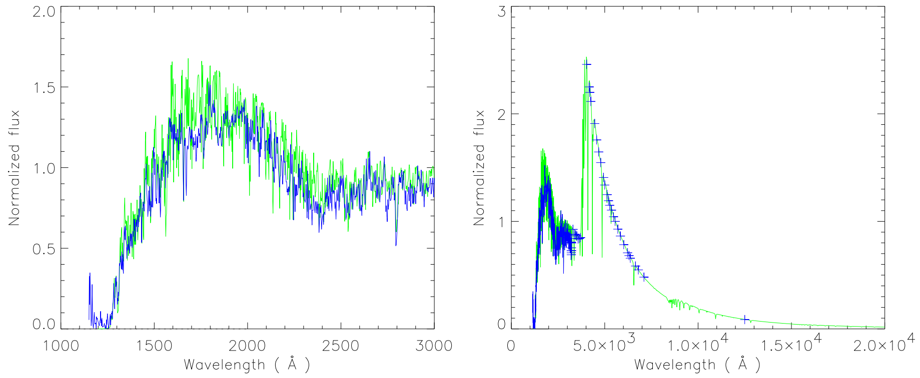
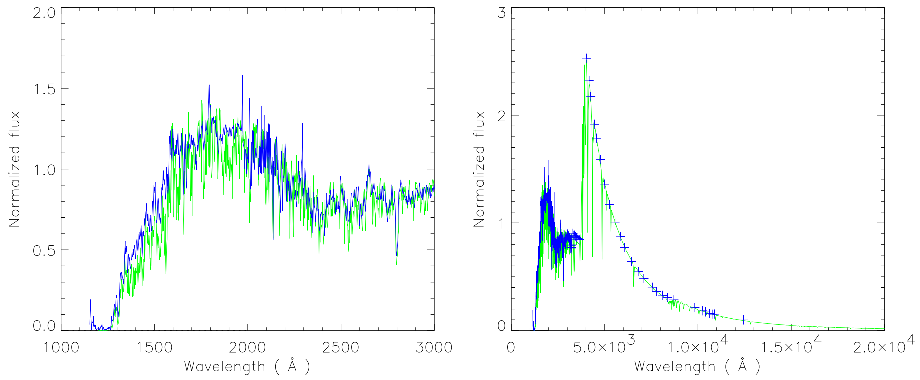



**Fig. 9.** Relative difference between our study and (Adelman et al. 2002) (Breger : +; Adelman : diamond).

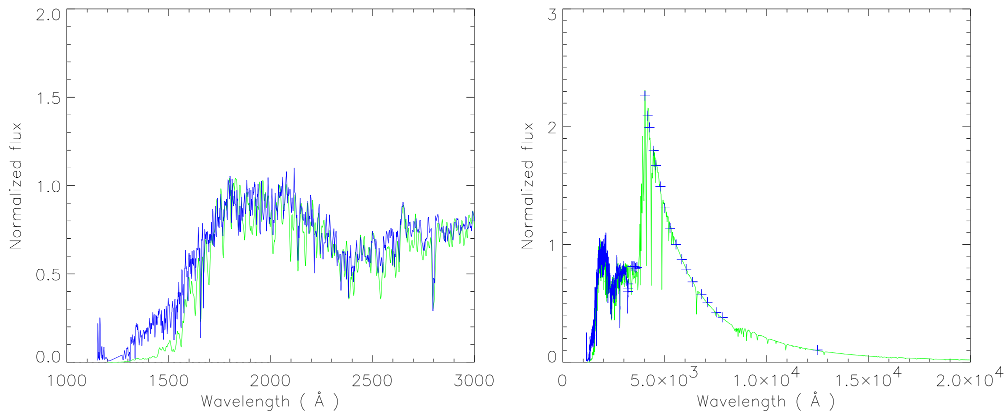



a) HD97633 - Adelman's data
A2V; $T_{eff}$ = 9162 K; log $g$ = 3, 62; $v \sin i$ = 15 km.s$^{-1}$.
Abundances : He, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Fe, Ni, Sr, Y and Ba from (Adelman 1996); C, N and O from (Roby et Lambert 1990); S, Mn and Zr from (Hill 1995); Co from (Adelman 2000); others : solar.

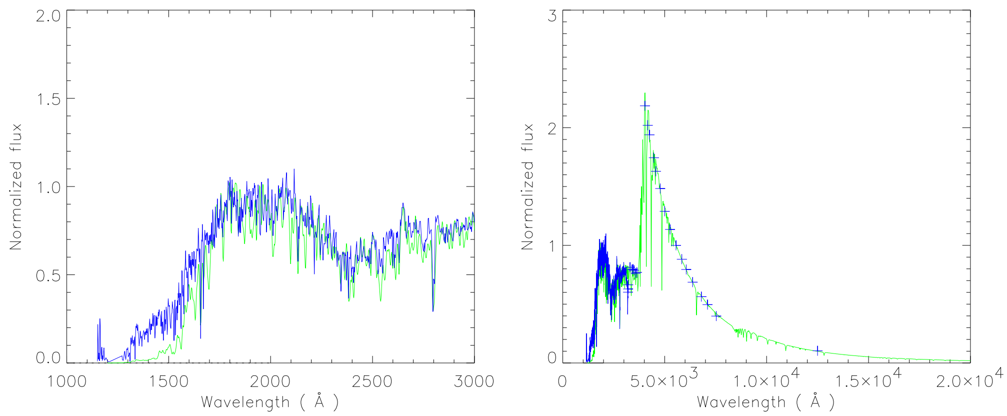



b) HD47105 - Breger's data
A0V; $T_{eff}$ = 8911 K; log $g$ = 3, 50; $v. \sin i$ = 10 km.s$^{-1}$.
Abundances : He, Mg, Al, Si, S, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Sr, Y, Zr and La from (Adelman 1988); C from (Lemke 1990); N from (Rentzsch-Holm 1997); O, Na and Ba from Adelman (1986); Cu and Zn from (Smith 1994); Ce from (Hill 1995); Hg from (Smith 1997); others : solar.

**Fig. 10.** Comparison between the observed spectral energy distribution (blue) and the theoretical spectral energy distribution (green) for the stars HD47105 and HD97633.




a) Adelman's data




b) Breger's data

A0V; $T_{eff}$ = 8911 K; $\log g = 3,50$; $v.\sin i = 10$ km.s$^{-1}$.
Abundances : solar.

**Fig. 11.** Comparison between the observed spectral energy distribution (blue) and the theoretical spectral energy distribution (green) for the star HD156164 : Adelman's data (Adelman et al. 1989) (top) and Breger's data (Breger 1976) (bottom).

as inputs the Strömgren photometry of the star. We use the values of Hauck and Mermilliod (Hauck & Mermilliod 1998). The code outputs the effective temperature, the logarithm decimal of the surface gravity and the interstellar extinction. The found value of the effective temperature is also used in input to the Planck's function for the extrapolation of the observed spectrum (see paragraph 4.3).

### 4.3. Integrated observed flux

To compute the integrated observed flux ($F_{obs}$), we proceed as follows : first, we interpolate the observed spectrum by a cubic spline function with a fixed step of 20 Å; we check the interpolation and if there is a problem, we make a linear interpolation between consecutive points (essentially in ultraviolet range or in the connection ultraviolet-visible) or we make an interpolation by a polynomial fraction (in the end of the visible and in infrared range). Then we extrapolate the observed spectrum above the last wavelength by the Planck's function (the used temperature is the initial effective temperature; see paragraph 4.2). Finally, we compute the integrated observed flux by trapezoidal integration.

### 4.4. Model atmospheres

To compute the synthetic flux, we use the Kurucz's code ATLAS (ATLAS9 or ATLAS12). This code needs as inputs: the effective temperature, the decimal logarithm of the surface gravity (the used surface gravity is retrieved from the code UVBYBETA (Napiwotzki et al. 1993); see paragraph 4.2). We assume a solar abundance and the local thermodynamic equilibrium. The code outputs the predicted flux which can be obtained in different ways :

1. we can interpolate from a grid of model atmospheres computed with ATLAS9;
2. we can at each iteration use ATLAS9 to compute the flux;
3. we can interpolate from a grid of model atmospheres computed with ATLAS12;
4. we can at each iteration use ATLAS12 to compute the flux.

Finally, we retained the second and the third method. The fourth needs too much computer time.

## 5. Results

### 5.1. Comparison between the results from the IRFM using ATLAS9 and ATLAS12

In figures 2 and 3, we compare the IRFM results (effective temperature and angular diameter) derived using ATLAS9 and derived using ATLAS12 for the two sets of data (Breger 1976; Adelman et al. 1989). We see that the use of either code leads to very similar effective temperatures and angular diameters for e Breger's data and for Adelman at al.'s data. For the effective temperature and the angular diameter, we find a linear correlation coefficient close to one and an average difference less than 20 $K$ for the effective temperature and less than 0.003 $mas$ for the angular diameter.

### 5.2. Comparison between the two sets of data

Figure 4 shows the comparison between Breger's data (Breger 1976) and Adelman et al.'s data (Adelman et al. 1989) for the effective temperature and for the angular diameter derived from the IRFM using ATLAS12. For the thirteen stars in common to both sample, the infrared flux method leads to the same effective temperatures and to the same angular diameters for Breger's data (Breger 1976) and for Adelmanet al.'s data (Adelman et al. 1989).

### 5.3. Strömgren photometry

In Fig. 5, we compare the infrared flux method effective temperature derived using ATLAS12 and the effective temperature derived from Strömgren's photometry (we use the Napiwotzki et al's code UVBYBETA (Napiwotzki et al. 1993); see paragraph 4.2). For the Breger's data (Breger 1976), the infrared flux method effective temperatures are lower by about 200 K than the effective temperatures derived from UVBYBETA. In the case of the Adelman et al. 's data (Adelman et al. 1989), they tend to be lower by about 150 K than the effective temperatures derived from UVBYBETA.

### 5.4. Comparison with previous studies

In figures 6 to 9, we compare our results with previous studies. Four studies used the infrared flux method (Blackwell & Lynas-Gray 1998, 1994; Blackwell et al. 1990; Varenne 1999). For the most of the common stars, the relative difference with our study is less than two percent. Another study (Di Benedetto 1998) determined effective temperature using a relation between effective temperature and Johnson broadband color ($V - K$). Our results are smaller than those of Di Benedetto for effective temperature above 8000 $K$ (most of the stars). For these values, the relative difference is between 2 and 4 % . The fourth (Adelman et al. 2002) determined effective temperature by adjustment of the Balmer's line H$\gamma$ region between the observed spectrum and the synthetic spectrum. In this case, the relative differences are generally less than three percent.

## 6. Observed versus theoretical SED

### 6.1. Theoretical energy distribution

To compute the theoretical energy distribution, we use ATLAS12. This code needs: an effective temperature taken from the IRFM results, a decimal logarithm of surface gravity computed with Napiwotzki's code UVBYBETA (see paragraph 4.2), elemental abundances retrieved from literature when available otherwise we assumed them to be solar and the microturbulent velocity also retrieved from literature. In output, we have a theoretical energy distribution from ultraviolet to infrared. Using the rotational velocity retrieved from literature and a value of 6 Å for the full width half maximum (FWHM) of the IUE (International Ultraviolet Explorer) cameras, those data are convolved using Hubeny's code ROTIN3 (retrieved from http://tlustyy.gsfc.nasa.gov/). The theoretical energy distribution can then be compared with the observed SED after normalizing at a reference wavelength.

### 6.2. Results

Figure 10 shows the comparison between observed and theoretical energy distribution for the star HD 97633 using data from (Adelman et al. 1989) and for the star HD 47105 using Breger's (1976) data. For these two stars, we can see a good agreement in the ultraviolet, visible and infrared range.

Figure 11 shows a comparison between observed and theoretical energy distribution for the star HD 156164 using Adelman et al. (1989) data and Breger's (1976) data. A clear disagreement is observed in the ultraviolet. The star, HD 156164, is a fast rotator with no abundance determinations in contrast with the two previous stars. So the discrepancy may be due to the assumption of solar composition.

## 7. Conclusion

We determined using the infrared flux method the effective temperature and the angular diameter for 41 main sequence A and F stars. The difference between effective temperatures derived using ATLAS9 models and using ATLAS12 interpolated models are not significant. The IRFM effective temperatures are smaller by about 200 K than the effective temperatures derived from the Strömgren's photometry. Adelman et al. (1989) data and Breger (1976) data for the thirteen common stars lead to same results in the effective temperature determination using the IRFM. Our study's values agree with the previous studies (Blackwell et al. 1979; Blackwell & Lynas-Gray 1994, 1998; Varenne 1999; Adelman et al. 2002) generally with a relative difference less than two percent. As for the effective temperatures derived from the Strömgren's photometry, the effective temperature derived from a relation between effective temperature and photometry (Di Benedetto 1998) is less than 200 K than the effective temperatures derived from the IRFM. The agreement between the observed SED and the theoretical SED is usually good if the fundamental parameters of the star are well known. However discrepancies may be observed in the far ultraviolet for a number of stars possibly because of non-solar chemical composition.

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