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TOWARDS USING OPTICAL/NIR PHOTOMETRY TO MEASURE THE TEMPERATURE OF O STARS

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RESUMEN

Tradicionalmente se ha dicho que no es posible usar fotometría visible/IR para medir la temperatura de las estrellas O. En esta contribución describimos los pasos necesarios para vencer los obstáculos existentes hasta la fecha y presentamos nuestros resultados preliminares para el caso de extinción baja.

ABSTRACT

It has been traditionally stated that it is not possible to use optical/NIR photometry to measure the temperatures of O stars. In this contribution we describe the steps required to overcome the hurdles that have prevented this from happening in the past and we present our preliminary results for the low-extinction case.

Key Words: stars: atmospheres — stars: early-type — stars: fundamental parameters

1. BACKGROUND

Hummer et al. (1988) declared two decades ago that "for hot stars ($T_{\rm eff} > 30\,000$ K), methods based on the integrated continuum flux are completely unreliable discriminators of the effective temperature". This statement has been subsequently reformulated to express that optical/NIR broad- or medium-band photometry cannot be used to determine the intrinsic properties of O stars. However, the data used by Hummer et al. (1988), as the authors themselves recognize, had observational uncertainties of 0.02 magnitudes in $E(B-V)$ and their flux calibration was only accurate to within 10% in the UV and 3% in the optical/NIR. Therefore, it is a legitimate question to ask whether optical/NIR can indeed be used to measure O-star temperatures if the precision and accuracy of our data are better than those amounts. In this contribution we present the steps required to reduce the uncertainties to a 1% level.

2. THE INTRINSIC COLORS OF O STARS

2.1. *Filter properties and zero-point determination*

The first required step is to calibrate the photometry by: (a) accurately measuring the reference SED (e.g. Vega), (b) determining the zero point that fine-tunes the correspondence between the observed and the reference SEDs, and (c) correctly defining the total (atmosphere + telescope + filter + detector) sensitivity curve of the system. (a) and (b) are needed in order to avoid systematic errors between different filters while (c) is needed to avoid "color terms" within a given filter. Some recent papers have managed to produce significant improvements in all of the above. Bohlin (2006) has used a combination of STIS spectrophotometry and Kurucz models to obtain a new SED for Vega that eliminates previous discrepancies between the results of different groups. Several other papers (Cohen et al. 2003; Maíz Apellániz 2005, 2006a,b; Holberg & Bergeron 2006) have analyzed different filter systems (Johnson, Strömgren, 2MASS...) to test the validity of the published sensitivity curves and to calculate the zero points. Interestingly, independent results for the same filter agree to within 1%, with the only outstanding exception of 2MASS K_s (Maíz Apellániz 2006b).

2.2. *Atmosphere models*

The second required step is to be able to use atmosphere models as inputs for the calculation of the intrinsic colors of O stars. The last five years have seen a significant increase in the detail of such models. The two most significant additions have been the inclusion of line blanketing by heavy elements and wind effects, the former being the one that has the largest effect in the optical and the latter the dominant one in the K band and longer wavelengths (when mass-loss rates are high, see Martins & Plez 2006). There are now grids for early B (Lanz & Hubeny 2006) and O (Lanz & Hubeny 2003; Martins et al. 2005) stars that cover the $T_{\rm eff} - \log g - Z$ space needed to derive synthetic broad-band colors for most hot stars. Furthermore, the synthetic colors from different models agree to within $\sim 1\%$, lending

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credence to their reliability and making them appropriate to be used as inputs for temperature determinations of early-type stars.

3. TEMPERATURE DETERMINATION TECHNIQUES: CHORIZOS

The traditional method for calculating $T_{\rm eff}$ from photometry has been through color-color diagrams and Q-parameter determinations. That strategy has several problems: (a) the slope of an extinction trajectory in a color-color plot depends on the initial SED; (b) the slope is not constant, either, as a function of the amount of extinction; and (c) it only allows the simultaneous use of information from two colors, hence being especially sensitive to systematic errors in the calibration and to deviations from the expected unextincted SEDs. All of the above can easily introduce considerable systematic errors in the determination of stellar temperatures but those problems are minimized when one uses a Bayesian code like CHORIZOS (Maíz Apellániz 2004), which can process information from many filters simultaneously without using the constant-slope Q approximation. This constitutes the third required step towards determining $T_{\rm eff}$ for O stars from photometry.

Taking into account all of the previous considerations and as a first test of the use of CHORIZOS to determine O-star temperatures, we are working on an analysis of optical/NIR photometry of low-extinction ($E(B-V) < 0.15$) O stars with CHORIZOS. Our preliminary results for six late-type O stars using Strömgren and 2MASS photometry fitting temperature, extinction, and extinction law simultaneously are shown in Figure 1. Using either TLUSTY or CMFGEN models as input SEDs yields photometric temperatures with random uncertainties of 1000–2000 K and systematic differences of $\lesssim 1000$ K with respect to the spectroscopic temperatures (based on the Martins et al. calibration [2005]). Kurucz SEDs yield similar random uncertainties but a larger systematic difference.

4. EXTINCTION LAW

The above results for low extinction are of little practical value for Galactic stars because most O stars in the Milky Way are moderately or heavily extinguished, with an extinction law that varies for different sightlines. Accurately accounting for extinction is the last required step in the process and, arguably, the hardest one to fulfill. The most commonly used family of optical/NIR Galactic extinction laws is that of Cardelli et al. (1989). However, that paper was based on an analysis of a small

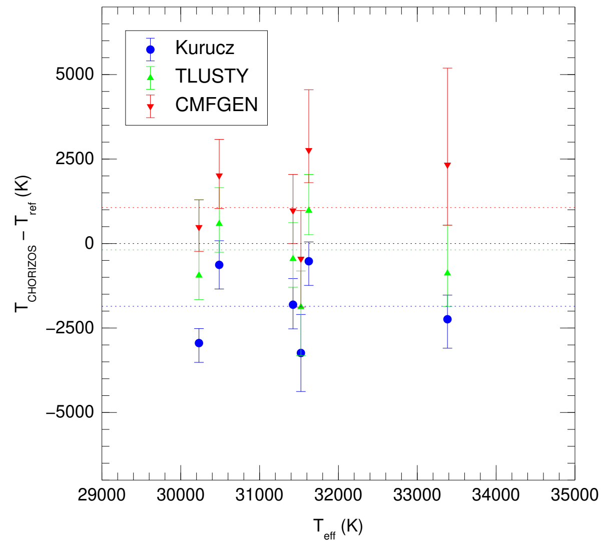

Fig. 1. Difference between photometric and spectroscopic temperature determinations for six low-extinction O stars using different SED families as inputs.

(29) sample of stars with only moderate extinction and used an unphysical seventh degree polynomial in $1/\lambda$ for the optical region. Hence, it is not possible to deredden observed photometry with the required accuracy for our goals ($\lesssim 1\%$) using the Cardelli et al. (1989) extinction law for $E(B-V) \gtrsim 0.5$. For that reason we believe that the time has come for the calculation of an alternative sightline-dependent Galactic optical/NIR extinction law. Some work has been recently done in the NIR (Moore et al. 2005; Nishiyama et al. 2006) but the optical has not been revised yet. We plan to do so in the incoming year using the data in the Galactic O star catalog as input.

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DISCUSSION

A. Herrero - Can the method be applied to supergiants with different mass losses?

J. Maíz Apellániz - Yes. It is all a matter of having the proper SED libraries available (the CHORIZOS code accepts any SED family as input). However, a different issue (that needs to be tested) is what is the filter combination that is most sensitive to that effect. Considering that the most important effect of different mass loss reates is an increase in the NIR fluxes, one would think that having more NIR filters in the mix would be a must. I would also worry about distinguishing between an increase in NIR flux due to an enhanced mass loss rate and the more classical IR excess due to circumstellar disks.

P. Massey - Two comments. First, I would have said that the calibration of STIS is not better than about 3% absolute and maybe 1% relative. Secondly, there are intrinsic variations in R_V that must limit how well you can do with your method.

J. Maíz Apellániz - (1) The absolute flux calibration of STIS is 1–2% accurate in the optical (in the FUV is worse $\sim 4\%$). The relative flux calibration, which depends on the uncertainty in the temperature of the three calibration WDs is considerably better: in the optical it is 0.2–0.4%. This is confirmed by the Tycho-2 $B_T - V_T$ results, where the scatter in the plot can be completely accounted by the uncertainties in the photometry (1–2%) without having to invoke an additional effect from the spectrophotometry. (2) Indeed there are intrinsic variations in R_V. That is why we combine optical and NIR photometry to measure R_V as one of the freee parameters. As an example, if we use Strömgren ubvry + 2MASS JH we have 5 independent colours. If we fix gravity and leave $T_{\rm eff}$, colour excess and R_V as free parameters, we still have two additional degress of freedom in CHORIZOS.

P. Williams - What is the sensitivity of the derived temperatures to uncertainty in luminosity class?

J. Maíz Apellániz - We have not explored this issue in full. Our preliminary results indicate that, if luminosity class is unknown, uncertainties in temperature for late-O stars should increase from 1000–2000 K to 3000–4000 K. However, I should note that the CHORIZOS output can always be constrained to a given gravity. For example if $\log g = 4.0$ then the temperature is $T_4 \pm \sigma_{T_4}$ and if $\log g = 3.0$ then the temperature is $T_3 \pm \sigma_{T_3}$.

Gloria proudly shows lastest results (or latest grandson picture) to Olga and Mónica.