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Letter to the Editor

α Centauri A in the far infrared★

First measurement of the temperature minimum of a star other than the Sun

R. Liseau[1], B. Montesinos[2], G. Olofsson[3], G. Bryden[4], J. P. Marshall[5], D. Ardila[6,7], A. Bayo Aran[8,9], W. C. Danchi[10], C. del Burgo[11], C. Eiroa[5], S. Ertel[12], M. C. W. Fridlund[13], A. V. Krivov[14], G. L. Pilbratt[13], A. Roberge[15], P. Thébault[16], J. Wiegert[1], and G. J. White[17,18]

[1] Department of Earth and Space Sciences, Chalmers University of Technology, Onsala Space Observatory, 439 92 Onsala, Sweden, e-mail: rene.liseau@chalmers.se
[2] Departamento de Astrofísica, Centro de Astrobiología (CAB, CSIC-INTA), Apartado 78, 28691 Villanueva de la Cañada, Madrid, Spain
[3] Department of Astronomy, Stockholm University, 106 91 Stockholm, Sweden
[4] Jet Propulsion Laboratory, M/S 169-506, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
[5] Departamento de Física Teórica, C-XI, Facultad de Ciencias, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain
[6] NASA Herschel Science Center, Infrared Processing and Analysis Center, MS 100-22, California Institute of Technology, Pasadena, CA 91125, USA
[7] Herschel Science Center – C11, European Space Agency (ESA), European Space Astronomy Centre (ESAC), PO Box 78, Villanueva de la Cañada, 28691 Madrid, Spain
[8] European Southern Observatory, Casilla 1900, Santiago 19, Chile
[9] Max Planck Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
[10] Astrophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[11] Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), Aptdo. Postal 51 y 216, 72000 Puebla, Pue., Mexico
[12] UJF-Grenoble 1/CNRS-INSU, Institut de Planétologie et d'Astrophysique de Grenoble (IPAG) UMR 5274, 38041 Grenoble, France
[13] Astrophysics Mission Division, Research and Scientific Support Department ESA, ESTEC, SRE-SA PO Box 299, Keplerlaan 1, 2200AG Noordwijk, The Netherlands
[14] Astrophysikalisches Institut und Universitätssternwarte, Friedrich-Schiller-Universität Jena, Schillergäßchen 2–3, 07745 Jena, Germany
[15] NASA Goddard Space Flight Center, Exoplanets and Stellar Astrophysics Laboratory, Code 667, Greenbelt, MD 20771, USA
[16] Laboratoire d'études spatiales et d'instrumentation en astrophysique, Observatoire de Paris, Section de Meudon, 5 place Jules Janssen, 92195 Meudon Cedex, France
[17] Dept. of Physics & Astronomy, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK
[18] Space Science & Technology Department, CCLRC Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK

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ABSTRACT

Context. Chromospheres and coronae are common phenomena on solar-type stars. Understanding the energy transfer to these heated atmospheric layers requires direct access to the relevant empirical data. Study of these structures has, by and large, been limited to the Sun thus far.

Aims. The region of the temperature reversal can be directly observed only in the far infrared and submillimetre spectral regime. We aim at determining the characteristics of the atmosphere in the region of the temperature minimum of the solar sister star α Cen A. As a bonus this will also provide a detailed mapping of the spectral energy distribution, i.e. knowledge that is crucial when searching for faint, Kuiper belt-like dust emission around other stars.

Methods. For the nearby binary system α Cen, stellar parameters are known with high accuracy from measurements. For the basic model parameters $T_{\rm eff}$, $\log g$ and [Fe/H], we interpolate stellar model atmospheres in the grid of *Gaia*/PHOENIX and compute the corresponding model for the G2 V star α Cen A. Comparison with photometric measurements shows excellent agreement between observed photospheric data in the optical and infrared. For longer wavelengths, the modelled spectral energy distribution is compared to *Spitzer*-MIPS, *Herschel*-PACS, *Herschel*-SPIRE, and APEX-LABOCA photometry. A specifically tailored Uppsala model based on the MARCS code and extending further in wavelength is used to gauge the emission characteristics of α Cen A in the far infared.

Results. Similar to the Sun, the far infrared (FIR) emission of α Cen A originates in the minimum temperature region above the stellar photosphere in the visible. However, in comparison with the solar case, the FIR photosphere of α Cen A appears marginally cooler, $T_{\rm min} \sim T_{160\,\mu{\rm m}} = 3920 \pm 375$ K. Beyond the minimum near 160 μm, the brightness temperatures increase, and this radiation very likely originates in warmer regions of the chromosphere of α Cen A.

Conclusions. To the best of our knowledge, this is the first time a temperature minimum has been directly measured on a main-sequence star other than the Sun.

Key words. stars: individual: α Cen – stars: atmospheres – stars: chromospheres – circumstellar matter – infrared: stars – submillimeter: stars

★ Based on observations with *Herschel*, which is an ESA space observatory with science instruments provided by the European-led Principal Investigator consortia and with important participation from NASA.

1. Introduction

The nearest stellar system to the Sun, α Centauri, is located at a distance of 1.3 pc (π = 747.1 ± 1.2 mas, Söderhjelm 1999). The physical binary is composed of two solar-like stars, the brighter of which, α Cen A (HIP 71683, HD 128620) a G2 V star, is often considered a "solar twin" (Cayrel de Strobel 1996; Meléndez et al. 2009). The companion, α Cen B, is of slightly later spectral type (K1) and has recently been found to host an Earth-mass planet (Dumusque et al. 2012). A possible link between chemical composition in the atmospheres of solar twins and the formation of systems containing rocky planets has been proposed by Meléndez et al. (2009).

No planet has yet been found around the primary, however, but like the Sun, α Cen A shows evidence of chromospheric emission in the optical and ultraviolet spectral regions (Ayres et al. 1976; Judge et al. 2004, and references therein) and should therefore also have atmospheric regions where the temperature gradient turns from negative to positive. There, the radial temperature profile of the star should exhibit a minimum. The rise in temperature beyond the "minimum temperature" region is caused by non-radiative energy being deposited, which leads to the heating of the higher atmospheric levels. The responsible physical processes are as yet unidentified and constitute the subject of intense study in solar physics and stellar astrophysics (Kalkofen 2007; Wedemeyer-Böhm et al. 2012; Cohen et al. 2005; Harper et al. 2013).

The minimum temperature of the solar atmosphere can only be measured directly in the far infrared (FIR; Eddy et al. 1969; Avrett 2003). In the wavelength region ~50−350 μm, the atmosphere becomes optically thick owing to the dominating H^- free-free opacity ($\propto\lambda^2$; Geltman 1965; Doughty & Fraser 1966) and, consequently, radiates at lower temperatures than the layers beneath (the photosphere in the visible, where $\tau_{0.5\,\mu m} > 1$). The precise location of the temperature minimum depends on the detailed structure of the atmosphere and can, with no convincing theory at hand, only be determined from direct measurement. It is in this region where non-radiative energy is deposited, and its physics is of strong general interest.

By analogy, this phenomenon can also be expected on α Cen A. We therefore set out to obtain such data with the *Herschel* Space Observatory (Pilbratt et al. 2010) in the FIR and complementary ones with the ground-based APEX submillimetre (submm) telescope. These facilities allow photometric imaging observations with high sensitivity. We present our findings in this Letter, which is organised as follows. In Sect. 2, the observations and reduction of the data are briefly described. The results are presented and discussed in Sect. 3, and in Sect. 4, our main conclusions are summarised.

2. Observations and data reduction

On July 29, 2011, PACS scan maps (Poglitsch et al. 2010) of α Cen were obtained for the DUNES programme (Eiroa et al., in prep.) at 100 μm and 160 μm at two array orientations (70° and 110°) to suppress detector striping. The selected scan speed was intermediate, i.e. 20″ s^{-1}, determining the *FWHM* at the two wavelengths (6.″8 and 11.″3, respectively). In addition, PACS 70 μm and 160 μm and SPIRE 250 μm, 350 μm and 500 μm (Griffin et al. 2010) data obtained as part of the Hi-GAL programme (Molinari et al. 2010) were also analysed (see http://herschel.esac.esa.int/Docs/SPIRE/html/spire_om.html#x1-980005.2.7). Our reduction work is thoroughly described by Eiroa et al. (in prep.) and Wiegert et al. (in prep.), and the PACS calibration scheme is reported in detail in http://herschel.esac.esa.int/twiki/bin/view/Public/PacsCalibrationWeb#PACS_instrument_and_calibration. Aperture corrections of the flux and sky noise corrections for correlated noise in the super-sampled images were done according to the technical notes PICC-ME-TN-037 and PICC-ME-TN-038 and https://nhscsci.ipac.caltech.edu/sc/index.php/Pacs/Ab-soluteCalibration. Both the relative and absolute positions in the sky are well known (Pourbaix et al. 2002, Table 1) and are shown, for the epochs of the observations, in Fig. 1 of Wiegert et al. (in prep.).

The LABOCA (Siringo et al. 2009, and http://www.apex-telescope.org/telescope/) observations of α Cen were made during two runs, viz. in November 10–13, 2007, and in September 19, 2009. The data associated with the programmes 380.C-3044(A) and 384.C-1025(A) were retrieved from the ESO archive. The map data were reduced and calibrated using the software package CRUSH 2 developed by Attila Kovács, see http://www.submm.caltech.edu/~sharc/crush/download.htm. The data have been smoothed with a Gaussian of *HPBW* = 13″, resulting in an effective *FWHM* = 23.″4. However, fluxes in Jy/beam are given for an *FWHM* = 19.″5.

All details regarding the data for both α Cen A and α Cen B will be presented in a forthcoming paper (Wiegert et al., in prep.).

Table 1. Photometry and radiation temperatures of α Centauri A.

$\lambda_{\rm eff}$ (μm)	S_ν (Jy)	$T_{\rm rad}$ (K)	Photometry & reference
0.440	2215 ± 41	5792 ± 19	*B* (1)
0.550	3640 ± 67	5830 ± 24	*V* (1)
0.790	4814 ± 89	5775 ± 32	*I* (1)
0.440	2356 ± 43	5856 ± 19	*B* (2)
0.550	3606 ± 66	5818 ± 23	*V* (2)
0.640	4259 ± 78	5787 ± 27	R_c (2)
0.790	4784 ± 88	5764 ± 32	I_c (2)
1.215	4658 ± 86	5928 ± 47	*J* (3)
1.654	3744 ± 69	6121 ± 60	*H* (3)
2.179	2561 ± 47	5994 ± 67	*K* (3)
3.547	1194 ± 22	5856 ± 78	*L* (3)
4.769	592 ± 11	4995 ± 69	*M* (3)
24	28.53 ± 0.58	4736 ± 91	MIPS (4)
70	3.40 ± 0.70	4599 ± 937	MIPS (4)
70	3.35 ± 0.028	4540 ± 37	PACS (5)
100	1.41 ± 0.05	3909 ± 135	PACS (6)
160	0.56 ± 0.06	3920 ± 394	* PACS (5), (6)
250	0.24 ± 0.05	4084 ± 845	*SPIRE (5)
350	0.145 ± 0.028	4822 ± 927	*SPIRE (5)
500	0.08 ± 0.03	5421 ± 2018	*SPIRE (5)
870	0.028 ± 0.007	5738 ± 1432	*LABOCA (7)

Notes. (*) Asterisks indicate values determined according to Eq. (1). (1) Hipparcos, (2) Bessell (1990), (3) Engels et al. (1981). (4) G. Bryden [priv. com.; *FWHM* (24 μm) = 6″, (70 μm) = 18″]. Binary separation on 9 April, 2005, 10.″4. (5) Hi-GAL: KPOT_smolinar_1, fields 314_0 & 316_0. *Herschel*-beams *FWHM* (70 μm) = 5.″6, (100 μm) = 6.″8, (160 μm) = 11.″3, (250 μm) = 17.″6, (350 μm) = 23.″9, (500 μm) = 35.″2. Binary separation on 21 August, 2010, 6.″3. (6) DUNES: KPOT_ceiroa_1. Binary separation 29 July, 2011, 5.″7. (7) 384.C-1025, 380.C-3044(A): *FWHM* (870 μm) = 19.″5. Binary separation 20–13 November, 2007, 8.″8 and 19 September, 2009, 7.″0.

3. Results and discussion

3.1. The spectral energy distribution of α Cen A

With the possible exception at 500 μm because of high background emission, α Centauri was clearly detected at all observed wavelengths. Flux densities for α Cen A with their statistical error estimates, from 0.4 to 870 μm, are provided in Table 1, together with the references to the photometry. For data where the binary was spatially unresolved (indicated by asterisks in the table), we used the PHOENIX models for both A and B to estimate the relative flux contributed by α Cen A (Wiegert et al., in prep.), viz.,

$$\frac{S_{\nu,\mathrm{A}}}{S_{\nu,\mathrm{A}}+S_{\nu,\mathrm{B}}}\begin{cases}\geq 0.69\ \&\ \leq 1.0 & \text{if } \lambda \leq 10\,\mu\mathrm{m}\\ = \text{const.} = 0.69 & \text{if } \lambda > 10\,\mu\mathrm{m}.\end{cases} \quad (1)$$

This is in fair agreement with the PACS measurement at 70 μm, where the pair is resolved and the flux ratio $S_\mathrm{A}/S_\mathrm{B} = 2.45 \pm 0.45$, as compared to the PHOENIX value of 2.25. We are aware that using a constant value may not yield the correct answer at all wavelengths. However, with its deeper and more compact convection zone α Cen B is the more active and more X-ray luminous star of the binary system (DeWarf et al. 2010). Assuming that the wavelength of the temperature minimum is similar for both stars yields for α Cen A an optically determined T_min that is higher by 20% (Ayres et al. 1976). We will keep this caveat in mind when searching for the temperature minimum in α Cen A.

The observations of α Cen are part of the DUNES programme (Eiroa et al., in prep.), which focusses on nearby solar-type stars. The observations with *Herschel*-PACS (Poglitsch et al. 2010) at 100 μm and 160 μm aim at detecting the stellar photospheres at an $S/N \geq 5$ at 100 μm. Prior to *Herschel*, and surprisingly perhaps, not many data at long wavelengths and of high photometric quality are available for these stars. One reason may be detector saturation problems due to their brightness (e.g., WISE bands W1–W4), another due to contamination in the large beams by confusing emission near the galactic plane (e.g., IRAS, ISO-PHOT, and AKARI data). Another issue is how to define the photosphere at FIR wavelengths, and this is, in fact, at the heart of this paper.

Because it is close-by (1.3 pc) and at a comparable age (4.8 Gyr), α Cen A is an excellent astrophysical laboratory for stars that are very similar to the Sun. From numerous literature sources, Torres et al. (2010) compiled the currently best available basic stellar parameters, and the estimated errors on the physical quantities are generally small (Table 2). However, whereas the tabulated uncertainty of the effective temperature of α Cen A is less than half a percent, the observed spread in Table 1 of Porto de Mello et al. (2008) does correspond to more than ten times this much. On the other hand, the radius given by Torres et al. (2010) is the one directly measured by Kervella et al. (2003) using interferometry (and corrected for limb darkening), with an error of 0.2% (Bigot et al. 2006). The mass has been obtained from asteroseismological measurements and is good to within 0.6% (Thévenin et al. 2002). However, it is also evident from the table that the twinship of α Cen A and the Sun is not close in every detail.

For such an impressive record of accuracy for the stellar parameters of the α Cen components it should be possible to construct theoretical model photospheres with which observations can be directly compared to a high level of precision. We report on FIR and submm observations, which should provide valuable constraints on the spectral energy distribution (SED). This could potentially be useful for gauging the temperature minimum at the base of the stellar chromosphere. A clear understanding of the latter is crucial when attempting to determine extremely low levels of cool circumstellar dust emission (Eiroa et al. 2011, and in prep.). Because of binary dynamics, dust is not expected to contribute to the stellar radiation from α Cen A (Wiegert et al., in prep., and references therein).

Table 2. Stellar parameters for α Cen A.

Parameter, P (unit)	Value of P		$(\Delta P/P)$	Ref.
	Sun	α Cen A	α Cen A	
Mass, M ($M_\odot$)	1.000	1.105	0.006	(1)
Radius, R ($R_\odot$)	1.000	1.224	0.002	(2)
Radiative luminosity, L ($L_\odot$)	1.000	1.549	0.042	(3)
Effective temperature, T_eff (K)	5770	5824	0.004	(3)
Surface gravity, $\log g$ (cgs)	4.440	4.306	0.001	(3)
Metallicity, [Fe/H]	0.000	+0.24	0.166	(3)
Age, $\mathcal{T}$ (Gyr)	4.57†	4.85	0.103	(1)

References. (1) Thévenin et al. (2002); (2) Kervella et al. (2003); (3) Torres et al. (2010). † Bonanno et al. (2002) give $\mathcal{T}_\odot = 4.57 \pm 0.11$ Gyr.

The atmosphere model for α Cen A has been computed by a 3D interpolation in the high-resolution PHOENIX grid for *Gaia* (Brott & Hauschildt 2005) and with the following parameters: (T_eff, $\log g$, [Fe/H]) = (5824 K, 4.306, +0.24), where $[\mathrm{Fe/H}]_\star = \log{(N_\mathrm{Fe}/N_\mathrm{H})_\star} - \log{(N_\mathrm{Fe}/N_\mathrm{H})_\odot}$. This model is shown in Fig. 1, together with the photometry that shows excellent agreement (Table 1). The photometry has not been used in the analysis, but serves to illustrate the good agreement between this model and the observations.

The PHOENIX model spectra are computed up to 45 μm. These models are used extensively by the DUNES programme and are therefore also exploited here. However, for this particular study, we have also used a specifically tailored model (the "Uppsala model") based on the MARCS code (Gustafsson et al. 2008), with, of course, exactly the same atmosphere parameters as before. This model computation extends to atmospheric layers more than 1500 km up, including those regions that emit predominantly around 200 μm. The infrared part of the Uppsala model is shown superposed onto the PHOENIX model in Fig. 1, where it can be seen that these two atmosphere models are virtually indistinguishable.

3.2. The temperature minimum of α Cen A

The observed FIR fluxes of α Cen A seem somewhat lower than in the model but appear to turn upward in the submm/mm bands (inset of Fig. 1). The 1D Uppsala (or PHOENIX) model describes stellar atmospheres in local thermodynamic equilibrium (LTE) and does not account for any temperature inversions. Both non-LTE effects and the change in the temperature gradient will influence the emergent spectrum (for details, see De la Luz et al. 2011). In the far infrared, this emission from the solar chromosphere exhibits a minimum in brightness temperature around 150 μm (Avrett 2003, and references therein). A chromosphere has also been observed for α Cen A in ultraviolet line emission (e.g., Judge et al. 2004). From the interpretation of the wings of the optical CaII K line, Ayres et al. (1976) deduced a value of $T_\mathrm{min}/T_\mathrm{eff} = 0.78$, similar to the solar value of 0.77. According

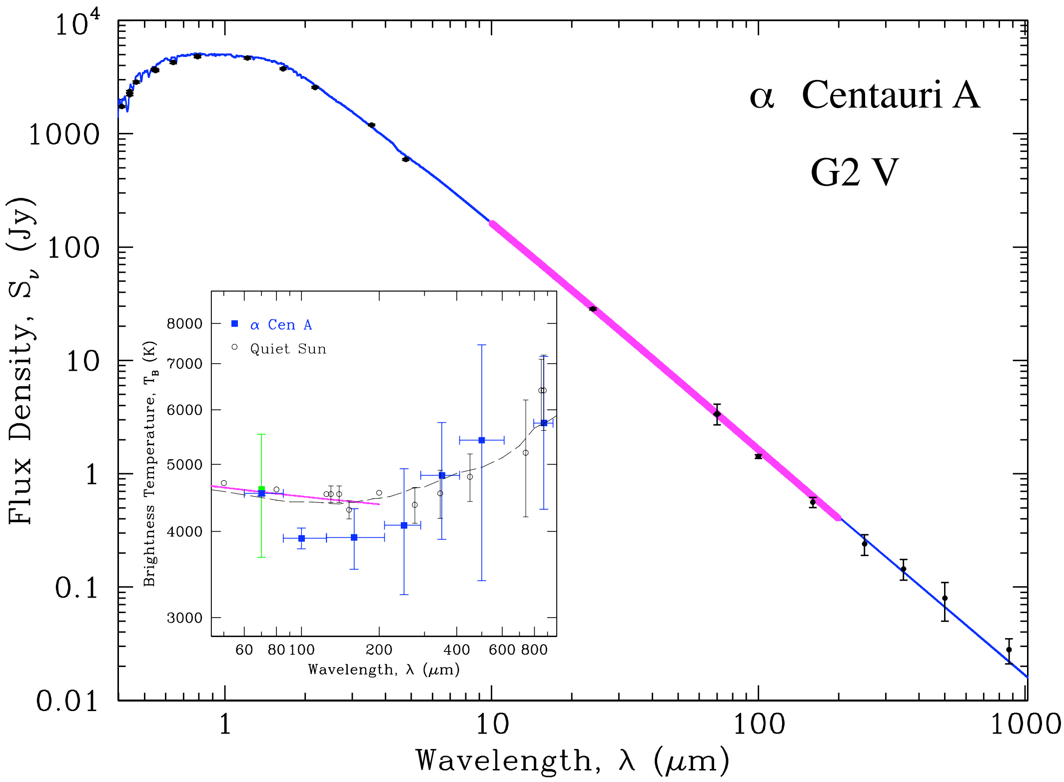

Fig. 1. The SED of α Cen A, where the blue line represents the PHOENIX model photosphere (computed up to $\lambda = 45\,\mu$m and Rayleigh-Jeans extrapolated beyond) and the thick (purple) line the Uppsala model photosphere (extending to $\lambda = 200\,\mu$m). Photometric data are shown with their 1σ error bar estimates (Table 1). The inset shows the brightness temperature of α Cen A (squares) and the Quiet Sun (circles) in the far infrared and submm. The solar data from the compilations by Gu et al. (1997) and Loukitcheva et al. (2004) are shown together with a semi-empirical chromosphere model for the Sun (Vernazza et al. 1981, black dashes: VAL IIIC). At $70\,\mu$m, the symbol with the larger error bar (green) represents the *Spitzer*-MIPS datum and filled (blue) squares *Herschel*-PACS/SPIRE and LABOCA data. Horizontal bars indicate filter widths.

to Judge et al. (2004), the level of activity of α Cen A is low and similar to that of the Sun in an intermediate stage of its cycle, and, on the basis of long-time X-ray monitoring, this apparent lack of variability was also emphasised by Ayres (2009).

We assume an atmosphere in radiative and hydrostatic equilibrium. The flux received at the Earth, S_ν, is related to the outward flux through the surface of the star, F_ν (e.g., Mihalas 1978), through

$$S_\nu = \pi \left(\frac{\phi_\nu}{2}\right)^2 \frac{F_\nu}{\pi}, \tag{2}$$

where ϕ_ν is the angular diameter of the stellar disc of radius R_ν, at a given frequency ν or wavelength λ, and as seen at a distance D. For these parallel stellar rays, a brightness temperature, $T_{\rm B}(\nu)$, can be defined through the Planck function by

$$F_\nu = \pi\, B_\nu(T_{\rm B}), \tag{3}$$

so that with $\phi_\nu/2 = R_\nu/D$,

$$T_{\rm B}(\nu) = \frac{h\,\nu}{k}\left[\ln\left(\frac{2\,\pi\,R_\nu^2\,h\,\nu^3}{D^2\,c^2\,S_\nu} + 1\right)\right]^{-1} . \tag{4}$$

In the far infrared, $R_{\rm FIR} = R_{0.5} + \Delta R$, where $R_{0.5}$ is the "photospheric" radius of the star. There the optical depth in the visible is unity ($\tau_{0.5} \sim 1$). The temperature minimum is found in regions higher up, where $\tau_{\rm FIR} > 1$ (but $\tau_{0.5} \ll 1$). It is straightforward to show (e.g., Tatebe & Townes 2006) that $\Delta R/R_{\rm FIR}$ is a few times 10^{-4}. Therefore, ΔR corresponds to some 500 km, and will per se not introduce any significant errors for stars like the Sun and α Cen A (luminosity class V) and in Eq. (3), we use $R_{\rm FIR} = R_{0.5}$ (cf. Table 2). However, over this distance, the density drops by an order of magnitude, making model computations increasingly difficult.

In Fig. 1, $T_{\rm B}(\nu)$ is shown for the Uppsala model photosphere, where LTE is assumed for the free-free H^- continuum, together with a semi-empirical chromospheric model of the quiet Sun (VAL IIIC, Vernazza et al. 1981). Solar data are shown as open circles and the observations of α Cen A as filled squares.

Using the Uppsala model, we find that $\chi_{100\,\mu{\rm m}} = -4.4$, where $\chi_\nu = (S_{\nu,\,\rm obs} - S_{\nu,\,\rm mod})/\sigma_\nu$. The difference in brightness temperature by 500 K in the 100 to 160 μm region could therefore be significant, and it cannot be excluded that in α Cen A the atmosphere becomes optically thick at higher, cooler levels than the model and that the structure is different from that in the Sun[1]. Important is, however, that the FIR-SED indeed goes through a minimum, since the brightness temperatures rise at longer wavelengths and, at e.g. 870 μm, H free-free emission from the stellar chromosphere appears to dominate.

In the solar atmosphere, the temperature minimum occurs around 150 μm. This also seems to be the case for α Cen A, where $T_{160\,\mu{\rm m}} = 3920 \pm 375$ K. It is customary to express the minimum temperature of the stellar atmosphere in terms of the effective temperature, $T_{\rm eff}$, and for α Cen A,

[1] Actually, a very similar scenario is also proposed for the Sun by Ayres (2002) in order to explain the lower $T_{\rm min}$ indicated by observations of infrared CO lines.

$T_{\rm min}/T_{\rm eff} = 0.67 \pm 0.06$. Ayres et al. (1976) had earlier, from Ca II K-line fitting, estimated this ratio as 0.78 to 0.79, for an assumed $T_{\rm eff}$ = 5770 to 5700 K, hence $T_{\rm min} \sim 4500$ K, which would indicate an "optical minimum temperature" about 500 K higher than what we determined from a direct measurement in the far infrared. This result may seem surprising, but we have to recall that similar is seen in the Sun, where different diagnostics yield a range in values of the minimum temperature by about 600 K (Avrett 2003). It is also worth remembering that even for the Sun, a unique model for its chromospheric emission has yet to be found (e.g., De la Luz et al. 2011). For its "sister star" α Cen A, future data at submm and mm wavelengths, for instance from ALMA, should contribute to better characterising the atmosphere of our nearest neighbour.

4. Conclusions

We successfully observed the far infrared energy distribution of the nearby G2 V star α Cen A with instruments aboard *Herschel* and from the ground. The observed radiation temperatures appear lower than what is expected on the basis of extensions of LTE stellar atmosphere models. Near 160 μm, the minimum temperature in the atmosphere of α Cen A, $T_{\rm min}/T_{\rm eff} = 0.67 \pm 0.06$, is marginally lower than the ratio of 0.73 observed in the Sun at 150 μm. At 870 μm, however, the emission from α Cen A appears to originate in regions at higher temperatures, as might be expected, viz. $T_{870\,\mu{\rm m}}/T_{\rm eff} = 1.0 \pm 0.2$. Temperature minimum regions will potentially lead to underestimating the amount of dust present in cold debris discs.

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