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Discovery of Blackbody Stars and the Accuracy of SDSS photometry

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Abstract. We discovered stars that show spectra very close to the blackbody radiation without any line features. We found 17 such stars out of 0.8 million stellar objects in the SDSS archive. The blackbody temperature is approximately 10^4K. We identify these stars as DB white dwarfs with the helium atmosphere, possibly with a trace amount of hydrogen, that yields nearly perfect blackbody spectrum, which is also confirmed with our later study. These stars can be used to test the accuracy of the AB zero point across different colour bands, in particular including the NIR pass bands. The zero points of SDSS photometry are verified to < 0.01 mag.

Keywords. blackbody star, SDSS photometry, photometric calibration

1. Introduction

We report on the discovery of stars that exhibit spectra very close to the blackbody radiation without any line features (Fukugita and Suzuki 2017) and their use for calibration of the photometric system, especially a verification of the Sloan Digital Sky Survey (SDSS) photometric system. We noticed one such stellar object in the sample of quasar candidates in the SDSS that is selected on the basis of colour-colour diagrams. While this stellar object was eventually dropt from the quasar candidate, our scrutiny of this object reveals that the spectrum does not resemble a quasar but it is a star showing very close to the blackbody radiation. We find that it shows a significant proper motion, so it must be a star located nearby.

2. Blackbody stars

We have then searched for similar objects in the entire database of SDSS. We find 22 objects that do not show any line features and are consistent with the blackbody spectrum ($\chi^2/\mathrm{dof} < 1.05$) out of 800,000 objects that are classified as stellar. Among the 22, five show spectra in excess of black body in the near infrared obseved with the WISE W1 channel, so circumstellar objects, say a companion star or dust surrounding the star, are suspected and are dropt from our sample of blackbody stars. This 20% fraction is consistent with that of NIR excess known for white dwrafs (Debes *et al.* 2011). These objects all have brightness $r > 17$. We found none brighter than this brightness. They are quite rare objects in the sky. Four examples are shown in Figure. 1 (spectra in left panels and broad-band photometry in right panels). The bottom panels show fractional offset from the fit with positions of possible absorption lines indicated. The one in Figure 2 is an example where we detect an IR excess, while the optical spectrum is close to blackbody.

All stars, except one, are catalogued in Gaia DR2 (Gaia DR2 2018). They show parallaxes from 4.4 to 14 mas, so their distances are 70-230 pc. Their brightness together with these parallaxes suggests that these stars are white dwarfs with helium atmosphere with temperature too low to develop absorption line features. One may take them as DC white

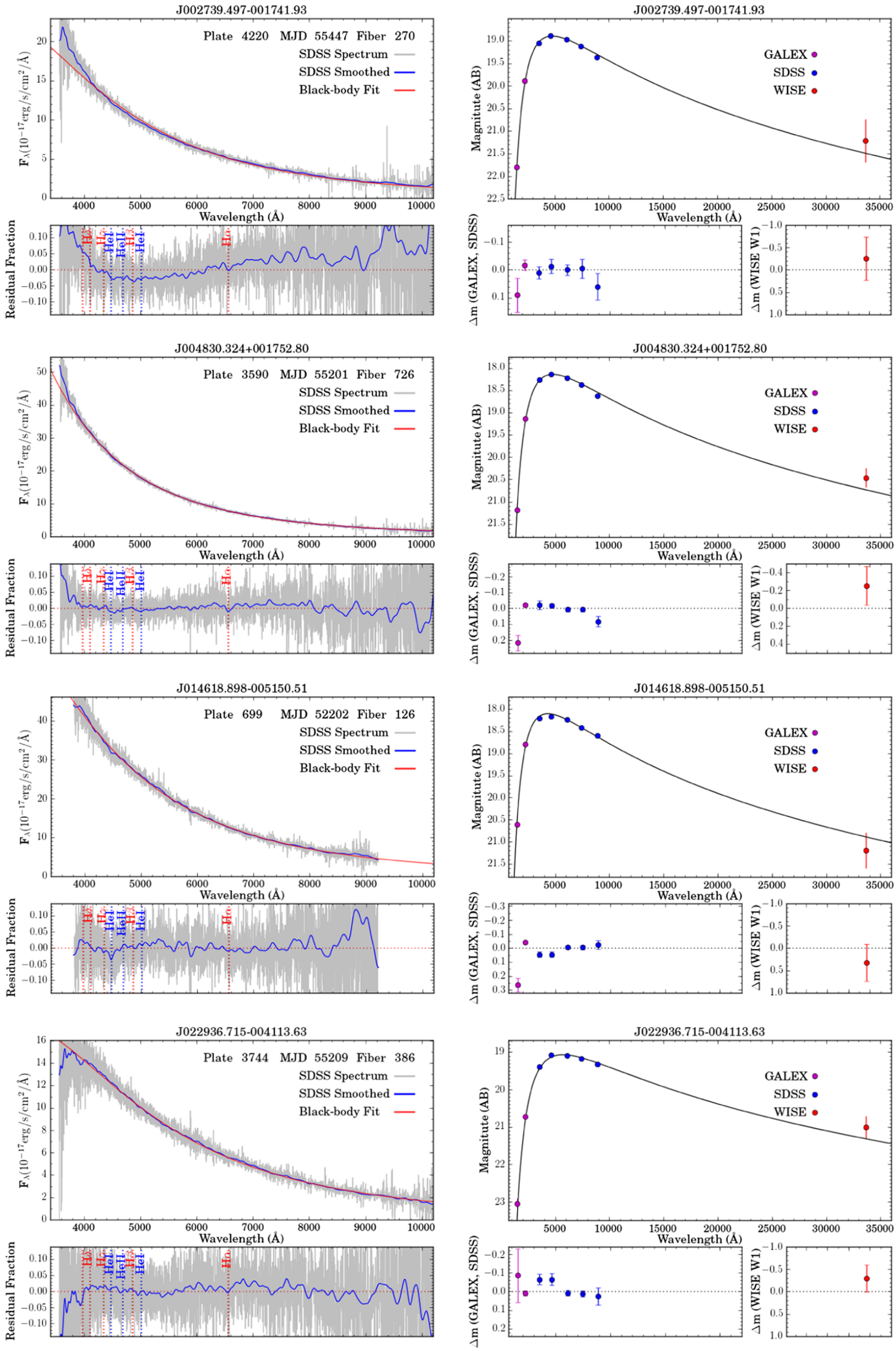

Figure 1. Four example spectra from the 17 blackbody stars we uncovered. In the left panels, observed spectra are indicated with grey and blue curves show smoothed spectra. Black-body fits are indicated with red. The right panels show the corresponding photometric data in the broad band from which our fit parameters are derived. In the bottom panels, the residuals (fractional values) from the fits are shown, with the positions of hydrogen and helium absorption lines indicated. Figures are taken from Suzuki & Fukugita (2017)

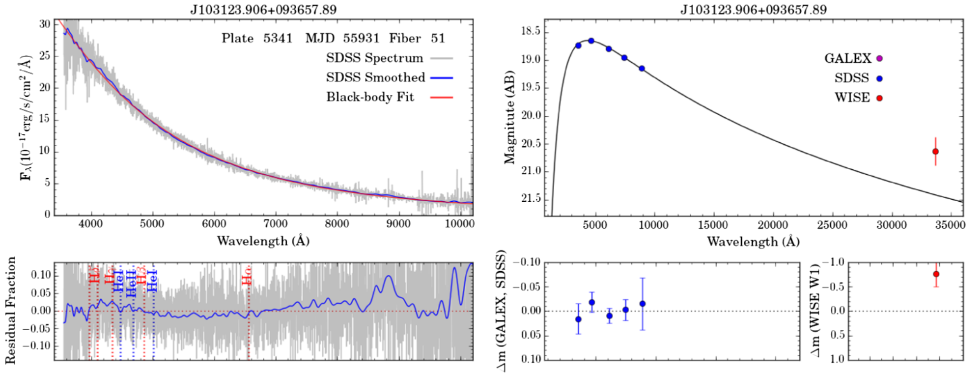

Figure 2. Example of the star that shows excess in the NIR, while the spectrum in the optical follows the blackbody spectrum. Figures are taken from Suzuki & Fukugita (2017).

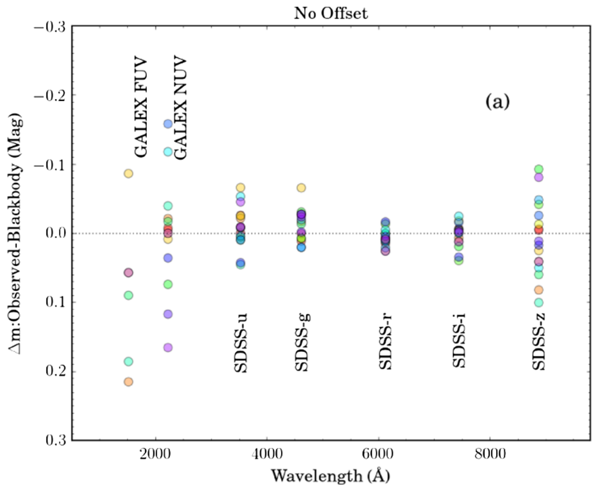

Figure 3. Residuals of the SDSS five-band photometric data and the GALEX NUV and FUV data from the blackbody fits in magnitude. Figure is taken from Suzuki & Fukugita (2017).

dwarfs by applying the observational criterion, but their physical nature are consistent with DB white dwarfs, as we confirmed in a later study (Serenelli *et al.* 2018). An accrate examination are carried out using more precise broad-band photometric data. The five band photometric data *ugriz* of SDSS, and also GALEX NUV plus FUV data, are fitted excellently with a blackbody spectrum with temperature 7400 to 12000K. Figure 3 shows the residual of our blackbody fit, showing that the deviation is small < 0.03 mag and random in nature: no systematic trend is noted.

One may think of the effect of reddening. Reddening is expected to be small at this distance (typically $E(B-V) \approx 0.02 - 0.03$ is expected), but, if any, it does not affect the proximity to blackbody, for its effect is parallel to the change in temperature: it only shifts the resulting temperature by a few hunded K lower upon the inclusion.

We found that the helium atmosphere model can yield precisely these blackbody spectra when the temperature is 8000K to 11000K, and in particular when helium is contaminated with a trace amount ($\approx 10^{-8} - 10^{-6}$) of hydrogen (Serenelli *et al.* 2018): see Figure 4. This hydrogen abundance is too small to detect its absorption features in current spectroscopic observations. We remark that the effective temperature of the atmosphere model turns out to be lower typically by 500 K than the temperature from

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Table 1. Mean of residuals from the black-body fit (Δm=data − black-body fit) to the 17 blackbody stars with the SDSS zero point.

Data Name	SDSS-u	SDSS-g	SDSS-r	SDSS-i	SDSS-z
Mean Residuals	−0.006±0.031	−0.008±0.025	0.007±0.012	0.002±0.017	0.003±0.052

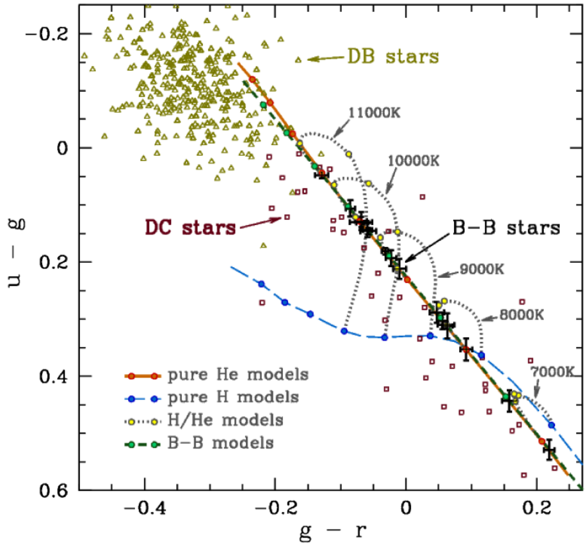

Figure 4. $u-g$ vs. $g-r$ colour-colour diagram of white dwarf stars. Our blackbody stars are shown with error bars. Green short-dashed line is the blackbody spectrum. Pure-He (red solid), pure-H (blue long-dashed) and H/He mixed atmosphere models (dotted) are also indicated (as in legends in the figure) in the range 12000-7000 K. Small circles on the curves show temperature in 1000K intervals. Those on the bridge between H and He models mark log $(N_{\rm H}/N_{\rm He}) = -2, -4, -6$. Figure is taken from Serenelli *et al.* (2018).

the blackbody fit. We note that all stars have temperature consistent with that in this range.

3. Accuracy of photometry

Irrespective of the physical nature, a significance of these blackbody stars lies in the fact that they can be used as photometric and spectrophotometric calibrators. As seen in Figure. 3 above the residual of our blackbody fit is typically a few times 0.01 mag, and is random in nature. When averaged over 17 stars, the departure from blackbody is smaller than 0.008 mag for all five colour bands (see Table 1). This means that these stars serve as excellent standards for photometry or spectrophotometry in optical bands. Their moderate faintness fits the standard to be used for 8-10 metre telescopes. GALEX photometry has larger errors (0.1 mag in NUV and 0.2 mag in FUV), but offsets are not detected.

We emphasise that the agreement of SDSS photometry of these stars (and GALEX photometry) with blackbody spectrum at this high accuracy, in turn, verifies the accuracy of the SDSS photomrtric system across the five colour bands. The SDSS photometric system, designated as AB_{95}, has been concocted from a number of elements Fukugita *et al.* (1996) and its accuracy is by no means evident but remained to be verified.

Briefly descibing, SDSS photometry is based on spectrophotometry of metal poor F-subdwarfs, BD+17°4708 and BD+26°2606, the spectra of which (F_ν) are relatively

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flat and show only very weak absorption features. This is in contrast to the prime calibrator α Lyr, which shows many conspicuous absorption lines and also the Balmer jump. Large parts of the spectrum of these SD stars is sufficently smooth. These BD spectra stand for, at the time, a handful of the most accurately measured SED, which were obtained by Oke & Gunn (1983) and further updated by Oke (1990). The Oke-Gunn standard, called AB_{79}, is based on the Vega SED of Hayes & Latham (1975) with the Oke & Schild (1970) zero point at 5480Å, upon which the original BD+17 and BD+26 SED were presented. We note that α Lyr is the only star, the flux of which is measured in the physical cgs units, thus can serve as the standard for the AB system.

In Fukugita *et al.* we revised the system to AB_{95}, using the Hayes (1985) compilation of αLyr supplemented with necessary short interpolations over some gaps using Castelli & Kurucz (1994) atmosphere. Oke-Gunn BD+17 SED was also updated with newer Oke's (1990) measurement. With these changes the definition of AB_{95} is by no means too straightforward. For this reason, I am particularly glad to see the agreement of the spectra of these stars across u to z bands with the blackbody stars, which verifies the accuracy of the SDSS photometric system across u to z bands being as good as ,0.01 mag, up to the absolute normalisation, which is yet to be verified.

As time passing there have been a few proposals that SDSS photometric zero points should be added with some constant varying from band to band from -0.04 to $+0.04$ mag to make the system closer to AB. We confirmed that such additions of offsets bring wiggles to the residuals of the blackbody fits, just by those added amounts. This means that the addition makes departure from the SB system only worse. This also includes the correction based on the CALSPEC standard.

Our final remark is that our blackbody stars can be used as flux calibrators, in particular in NIR photometry, for which good AB standards lack. An important feature is that the AB flux in NIR thus obtained should obviously be consistent with the AB system used in the optical bands.

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References

Castelli, F., & Kurucz, R. L. 1994, A&Ap, 281, 817
Debes, J. H., Hoard, D. W., Wachter, S., Leisawitz, D. T., & Cohen, M. 2011, ApJS, 197, 38
Fukugita, M., Ichikawa, T., Gunn, J. E., *et al.* 1996, AJ, 111, 1748
Gaia Collaboration, Brown, A. G. A., Vallenari, A., *et al.* 2018, A&Ap, 616, A1
Hayes, D. S. 1985, Calibration of Fundamental Stellar Quantities, 111, 225
Hayes, D. S., & Latham, D. W. 1975, ApJ, 197, 593
Oke, J. B. 1990, AJ, 99, 1621
Oke, J. B., & Gunn, J. E. 1983, ApJ, 266, 713
Oke, J. B., & Schild, R. E. 1970, ApJ, 161, 1015
Serenelli, A., Rohrmann, R., & Fukugita, M. 2018, arXiv:1804.01236
Suzuki, N., & Fukugita, M. 2017, arXiv:1711.01122, AJ in press (2018)

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