A&A 400, L13–L16 (2003)
DOI: 10.1051/0004-6361:20030132

Astronomy & Astrophysics

Model atmosphere analysis of the extreme DQ white dwarf GSC2U J131147.2+292348

D. Carollo[1], D. Koester[2], A. Spagna[1], M. G. Lattanzi[1], and S. T. Hodgkin[3]

[1] INAF, Osservatorio Astronomico di Torino, 10025 Pino Torinese, Italy
[2] Institut für Theoretische Physik und Astrophysik, Universität Kiel, 24098 Kiel, Germany
[3] Cambridge Astronomical Survey Unit, Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK

Received 12 January 2003 / Accepted 28 January 2003

Abstract. A new model atmosphere analysis for the peculiar DQ white dwarf discovered by Carollo et al. (2002) is presented. The effective temperature and carbon abundance have been estimated by fitting both the photometric data ($UB_JVR_FI_NJHK$) and a low resolution spectrum ($3500 < \lambda < 7500$ Å) with a new model grid for helium-rich white dwarfs with traces of carbon (DQ stars). We estimate $T_{\rm eff} \simeq 5120 \pm 200$ K and $\log[{\rm C/He}] \simeq -5.8 \pm 0.5$, which make GSC2U J131147.2+292348 the coolest DQ star ever observed. This result indicates that the hypothetical transition from C_2 to C_2H molecules around $T_{\rm eff} = 6000$ K, which was inferred to explain the absence of DQ stars at lower temperatures, needs to be reconsidered.

Key words. white dwarfs – techniques: spectroscopic – stars: kinematics – stars: individual: GSC2U J131147.2+292348

1. Introduction

The presence of carbon in the atmospheres of some non-DA white dwarfs (defined as spectral type DQ) is generally explained by the convective dredge-up from the stellar core to the outer photospheric layers (Koester et al. 1982; Pelletier et al. 1986). C_2 molecules are responsible for the absorption bands (e.g. in particular the Swan bands) which are the typical signature of the DQ stars. The spectral energy distribution of these stars changes significantly as a function of the effective temperature, $T_{\rm eff}$, and carbon abundance, [C/He], as shown by the theoretical atmosphere models of Koester et al. (1982) and Wegner & Yackovich (1984). Typically, strong absorption bands are expected for the coolest DQ stars, even in the case of low carbon abundances.

However, past surveys revealed DQ stars with effective temperature above 6500 K only (Bergeron et al. 1997). The existence of this cut-off is not well understood. In fact, if cool DQ stars with $T_{\rm eff} < 6500$ K do exist, their strong Swan bands would result in peculiar colors and spectra which should make these objects easily recognizable.

On the other hand, at low temperature carbon can be present also in a different form, as C_2H molecules, if some hydrogen is also present. The electronic transition spectra of the C_2H are not known from theory or laboratory experiments, but the observed spectra of the few known C_2H stars show molecular absorption bands similar to the Swan bands shifted by about 150 Å toward the blue. This shift cannot be explained as an effect of pressure shift of the Swan bands in a helium dominated atmosphere (Bergeron et al. 1994) or as a displacement due to a magnetic field (Schmidt et al. 1995). The presence of a certain fraction of hydrogen in the atmosphere of such non-DA white dwarfs can also be inferred by the collision induced absorption in the near IR due to H_2 molecules, as in the case of LHS 1126.

These observations suggest the hypothesis that DQ white dwarfs turn into C_2H stars when $T_{\rm eff}$ is below 6500 K, due to a not well identified physical mechanism that should inject hydrogen[1] in the He-dominated atmosphere of the DQ stars (Bergeron et al. 1997, 2001).

Recently, Carollo et al. (2002) discovered GSC2U J131147.2+292348 during a proper motion survey for halo white dwarfs based on the photographic material used for the construction of the GSC-II (McLean et al. 2000). As shown in Fig. 2 of Carollo et al. (2002), this object appears as a very peculiar carbon rich white dwarf due to the simultaneous presence of strong C_2 Deslandres-d'Azambuja and Swan bands, with an evident depression of the continuum in

Send offprint requests to: D. Carollo, e-mail: carollo@to.astro.it

[1] The evolution of the "missing" cool DQ stars is related to the more general problem of the non-DA gap which derives from the apparent lack of non-DA stars observed with temperature $5100 \lesssim T_{\rm eff} \lesssim 6100$ K. At the moment, the cause of this effect, which could depend on the physical and chemical evolution of the white dwarf atmospheres during the cooling phases as well as on not sufficiently understood input physics, is not well established (see e.g. Bergeron et al. 1997; Malo et al. 1999).

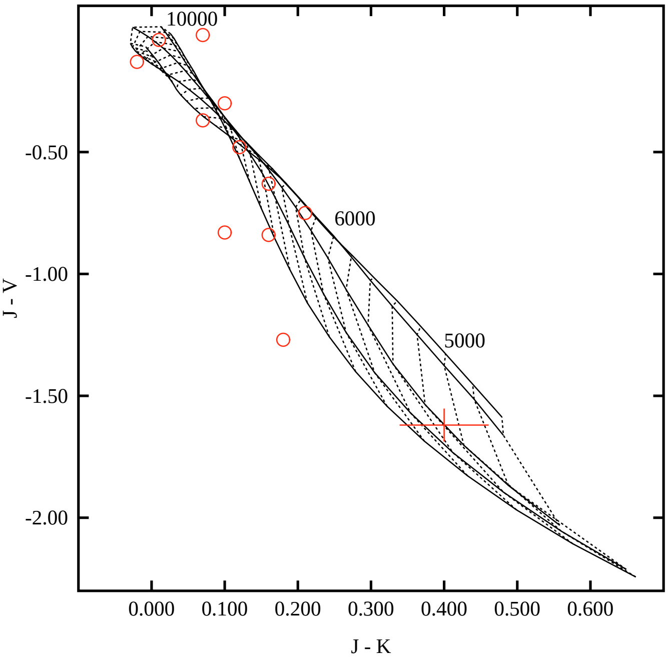

Fig. 1. Two-color diagram constructed from VJK. For the theoretical predictions the continuous lines are lines of constant carbon abundance from log[C/He] = −8 (top) to −4 (bottom); dotted lines are lines of constant effective temperature as described in the text. The cross marks GSC2U J131147.2+292348 which is the coolest object near 5100 K, while the circles indicate other DQ stars.

the Swan region between 4500 and 6200 Å. No other DQ star shows both these extreme features.

GSC2U J131147.2+292348 represents an enigma as well as an opportunity to test the predictions of the scenario discussed above for these objects. In fact, temperatures as low as 6000 K were already estimated by Carollo et al. (2002) by means of a simple spectral analysis. As described in the next sections, here we adopt a more sophisticated fitting technique based on new atmosphere models in order to estimate accurately the temperature and composition of this object. The new results confirm cool values of the temperature, $T_{\rm eff} \simeq 5100$ K, and the implications of this result will be briefly discussed.

2. Model atmosphere analysis of GSC2U J131147.2+292348

GSC2U J131147.2+292348 shows extremely strong bands of the C_2 molecule, especially the Swan and Deslandres-d'Azambuja band systems in the optical range. As these bands obviously block a significant fraction of the total flux, they will influence the temperature structure of the atmosphere models. We have therefore calculated a new grid of model atmospheres, which takes into account the blanketing effect of 537 bands from the Swan, Deslandres-d'Azambuja, Fox-Herzberg, Phillips, and Ballik-Ramsay systems, as well as numerous atomic carbon lines and the resonance lines of He I in the EUV. The general molecular data were taken from Huber & Herzberg (1979), the Franck-Condon factors for the vibrational transitions from various sources (Krishnaswamy & Odell 1977; Dwivedi et al. 1978; Spindler 1965; Sharp 1984). Molecular absorption is treated with the "just overlapping line approximation (JOLA)" in the version as described in Zeidler-K.T. & Koester (1982).

The general procedures and input physics of the model atmosphere calculations are very similar to the description in Finley et al. (1997). As it is practically impossible for very cool white dwarfs to determine effective temperature, surface gravity, and in our case the carbon abundance simultaneously, we have held $\log g$ fixed at the canonical value of 8.00. $T_{\rm eff}$ for the grid ranges from 10 000 to 4600 K, the abundance ratio log[C/He] by numbers from −8 to −4.

2.1. Magnitudes and colors

For cool white dwarfs magnitudes and colors, especially in the infrared, are very useful for the determination of atmospheric parameters, a method pioneered by Bergeron et al. (1997).

Since magnitudes in both the standard and photographic system, with a spectral coverage from the ultraviolet to the near IR, have been observed for GSC2U J131147.2+292348, we have also calculated theoretical magnitudes for our model grid. We adopted *U, V* from the photographic photometry given by Moreau & Reboul (1995), while Carollo et al. (2002) provided photographic B_J, R_F and I_N in the natural photographic system of the POSS-II plates, plus standard JHK photometry from observations carried out at the 4-m TNG (La Palma). The methods and the magnitude zeropoints used for the *UV-JHK* bandpasses in the standard Johnson system are described in detail in Zuckerman et al. (2003). For the photographic B_J, R_F and I_N (approximately corresponding to the Johnson-Cousins $B(RI)_{\rm c}$) we have used the same transmission curves adopted for the photometric calibration of the GSC-II plates and determined the zeropoints from integrations over the Vega flux as obtained from the STScI archive.

The available magnitudes from U to K completely determine the energy distribution of GSC2U J131147.2+292348. We have used our automatic least squares fitting routine, described in Zuckerman et al. (2003) to determine the best fitting parameters within the $T_{\rm eff}$ - log[C/He] grid, resulting in an extremely low effective temperature around 5000 K (Table 1). The first row in the table gives the observed magnitudes, the second the assumed errors. The third row are the theoretical predictions for the best fit parameters $T_{\rm eff} = 4980$ K, log[C/He] = −6.17.

As an internal check, we tested the effect of fitting the physical parameters with only the standard *UVJHK* photometry with respect to the global solution including also the B_J, R_F and I_N magnitudes. The last two rows of Table 1 show that the parameters change only very little, indicating that the GSC-II magnitudes are certainly very consistent with the overall energy distribution.

Figure 1 shows the position of GSC2U J131147.2+292348 in a special two-color diagram $J-V$ vs. $J-K$, using only standard magnitudes to be able to compare with other known DQ white dwarfs. Continuous lines are lines of constant carbon abundance, from −4.0 to −8.0, dotted lines are lines of constant effective temperature from 4600 K to 10 000 K in steps

Table 1. Observed standard and photographic magnitudes for GSC2U J131147.2+292348 and theoretical fits.

observations	T_{eff}/log[C/He]	U	B_J	V	R_F	I_N	J	H	K
UBVRIJHK		19.15	19.60	19.10	18.10	17.50	17.48	17.13	17.08
errors		0.15	0.15	0.15	0.15	0.15	0.05	0.10	0.12
model	4980/–6.17	19.06	19.59	19.11	18.19	17.81	17.44	17.18	17.02
UVJHK		19.15		19.10			17.48	17.13	17.08
model	4955/–6.32	19.15		19.10			17.47	17.20	17.04

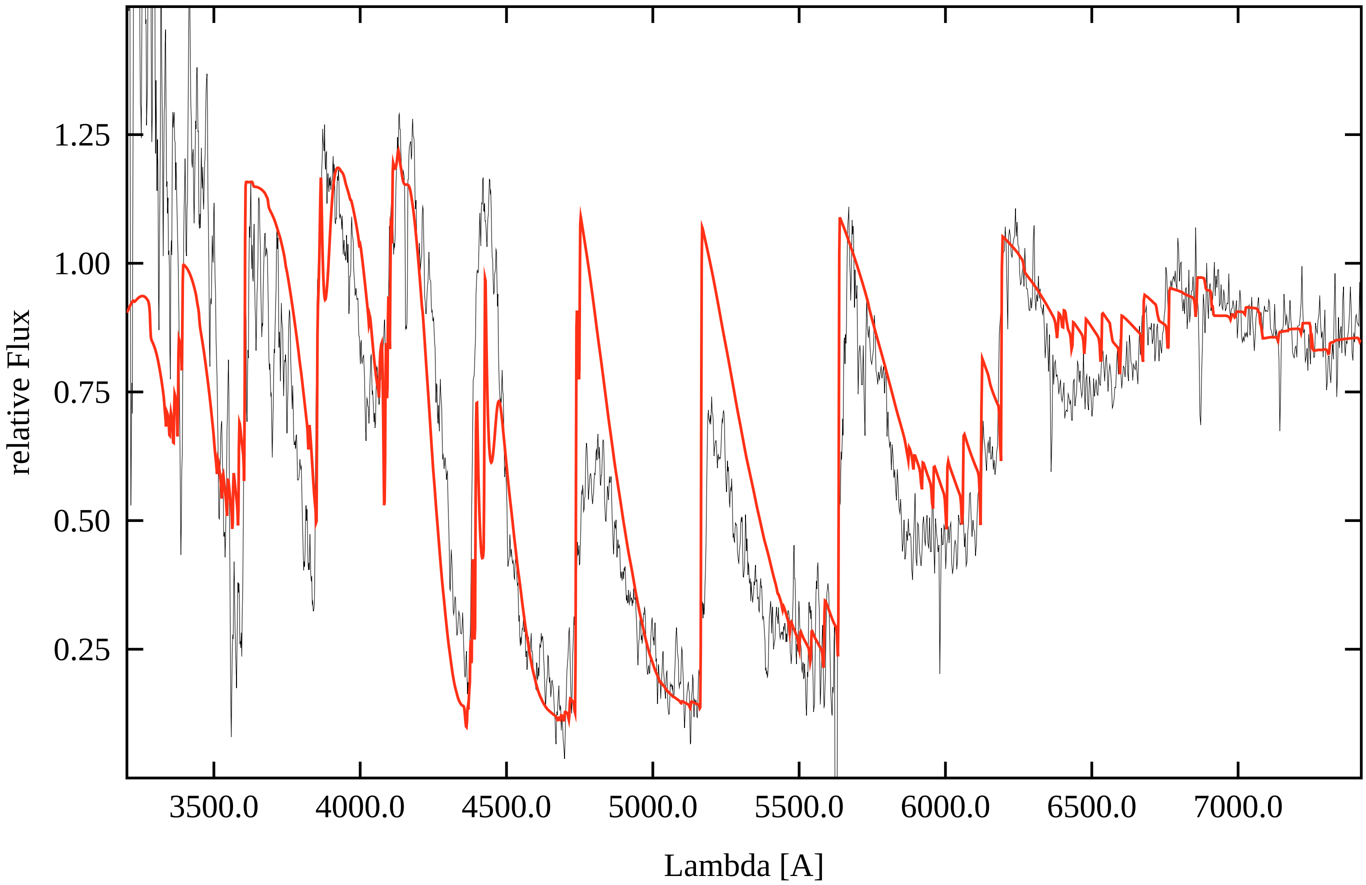

Fig. 2. Observed spectrum of GSC2U J131147.2+292348 (thin line) and theoretical model (thick line).

of 200 K. As can be seen, this diagram is not very useful at temperatures above 7000 K, because of the competing direct effect of flux blocking and the indirect blanketing effect on the temperature structure. However, in the range 4600–6600 K and the abundances considered here, the diagram gives a clear indication of the atmospheric parameters. The cross at the lowest temperatures is GSC2U J131147.2+292348, for which we would determine $T_{\mathrm{eff}} = 5100$, $\log[\mathrm{C/He}] = -6.0$ from this position. The other 11 circles are observations of DQ white dwarfs from Bergeron et al. (1997) and Bergeron et al. (2001), which clearly are all much hotter, in agreement with temperatures derived in Bergeron et al. (1997).

2.2. Spectral fitting

The spectrum of GSC2U J131147.2+292348 has been described in detail in Carollo et al. (2002). They concluded that the extremely strong bands of the Swan and Deslandres-d'Azambuja systems in the optical range are compatible with models calculated in Wegner & Yackovich (1984), whereas the energy distribution in the infrared could be explained by a blackbody distribution of around 6000 K. With our consistent model atmospheres available, we can apply our standard spectral fitting technique (e.g. Koester et al. 2001) with a Levenberg-Marquard algorithm (Press et al. 1992) to find the minimum χ^2 solution, using T_{eff} and log[C/He] as two free fitting parameters instead of the usual T_{eff} and $\log g$ in the case of DA or DB white dwarfs. The quasi continuum was forced to fit the model at two positions (around 4150 and 7000 Å), allowing for remaining small calibration errors of the spectral flux. The resulting parameters for the best fit are $T_{\mathrm{eff}} = 5200$ K, $\log[\mathrm{C/He}] = -5.53$. Figure 2 shows the observed spectrum together with the theoretical model corresponding to these parameters. Qualitatively, the theoretical model describes the main features of the spectrum, in particular the very strong band systems. In the details discrepancies remain, which may have a number of origins: the temperature structure of the models, the equation of state in these very high pressure atmospheres, and, most likely, missing bands, due to unkown Franck-Condon factors for the bands with highly excited lower levels, which are weak at laboratory conditions, but may be important in the much hotter stellar atmosphere. Nevertheless, we consider the fit satisfactory and a confirmation of the low temperatures derived from the photometry.

2.3. Results and conclusion

The fitting procedure for the photometry as well as for the spectrum provides formal errors, derived from the assumed statistical errors of the observations. These are very small – typically 30–40 K for $T_{\rm eff}$ and 0.05 for log[C/He] – and definitely unrealistic, because the errors are dominated by systematic errors of the models and reductions. These errors can be estimated only very roughly, taking the differences between the solutions from photometry and spectrum as a guide. Since we believe that the spectral result is more reliable, we give it double weight and take as the final result for the atmospheric parameters $T_{\rm eff} = 5120 \pm 200$ K and $\log[{\rm C/He}] = -5.8 \pm 0.5$. The distance modulus obtained from the photometric solution is 3.69 mag, corresponding to a distance of 55 pc and to a tangential velocity $V_{\rm tan} = 4.74 \cdot \mu\, d \simeq 125$ km s^{-1} ($\mu = 0.48''$ yr^{-1}). Adopting the same kinematics assumptions as in Carollo et al. (2002), we obtain galactic velocity components with respect to the LRS, $(U, V) \simeq (-115, -1)$ km s^{-1}. These values are well consistent with the velocity ellipsoid of the galactic halo (1σ) and are still consistent with the thick disk kinematics (2σ), while the membership of GSC2U J131147.2+292348 to the thin disk appears much less probable.

However, one needs to keep in mind that the results have been derived using a fixed surface gravity of $\log g = 8.00$. While we do not expect the atmospheric parameters to change much with $\log g$, the distance modulus depends of course on the radius of the star, which depends strongly on the assumed surface gravity. Allowing for a plausible range of 7.5–8.5, the radius could be different up to ±30%, with the same change resulting for the distance and velocity.

With $T_{\rm eff}$ about 5100 K this star is by far the coolest known "normal" DQ object. It is below the cutoff seen by Bergeron et al. (1997) near 6500 K and also below or at least at the lower edge of the so-called non-DA gap. It cannot be true therefore that all DQ turn into C_2H stars when they cool down, and one obvious explanation could be that some stars completely avoid any accretion of hydrogen, which is a prerequisite for the formation of this molecule. However, the final explanation of this puzzle as well as others concerning the non-DA gap will likely need to wait for the discovery of more similar objects from the ongoing large scale survey like the SDSS.

Acknowledgements. The authors are grateful to B. J. McLean for his constant support of this program. The GSC II is a joint project of the Space Telescope Science Institute and the Osservatorio Astronomico di Torino. Space Telescope Science Institute is operated by AURA for NASA under contract NAS5-26555. Partial financial support to this research comes from the Italian CNAA and the Italian Ministry of Research (MIUR) through the COFIN-2001 program.

This work is based on observations made with the Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Centro Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias, and also based on observations made with the William Herschel Telescope operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.

References

Bergeron, P., Leggett, S. K., & Ruiz, M. 2001, ApJS, 133, 413
Bergeron, P., Ruiz, M. T., & Leggett, S. K. 1997, ApJS, 108, 339
Carollo, D., Hodgkin, S. T., Spagna, A., et al. 2002, A&A, 393, 45
Dwivedi, P. H., Branch, D., & Huffaker, J. N. 1978, ApJS, 36, 573
Finley, D. S., Koester, D., & Basri, G. 1997, ApJ, 488, 375
Huber, K. P., & Herzberg, G. 1979, Constants of Diatomic Molecules (New York: Van Nostrand)
Koester, D. S., Weidemann, V., & Zeidler-K.T., E.-M. 1982, A&A, 116, 147
Koester, D., Napiwotzki, R., Christlieb, N., et al. 2001, A&A, 378, 556
Krishna Swamy, K. S., & O'Dell, C. R. 1977, ApJ, 216, 158
Moreau, O., & Reboul, H. 1995, A&AS, 111, 169
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical recipes in FORTRAN, The art of scientific computing (Cambridge University Press), 2nd ed.
Schmidt, G. D., Bergeron, P., & Fegley, B. Jr 1995, ApJ, 443, 274
Sharp, C. M. 1984, A&AS, 55, 33
Spindler, R. J. 1965, JQSRT, 5, 165
Wegner, G., & Yackovich, F. H. 1984, ApJ, 284, 257
Zeidler-K.T., E.-M., & Koester, D. 1982, A&A, 113, 173
Zuckerman, B., Koester, D., Reid, I. N., & Hünsch, M. 2003, in preparation