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A new hot DA white dwarf in a region of exceptionally low H I density

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ABSTRACT

We report the discovery of the hot DA white dwarf RE 0457 − 281 which has the lowest line-of-sight neutral hydrogen column density yet measured. The star was found independently by the *ROSAT* EUV, Montreal–Cambridge–Tololo and Edinburgh–Cape surveys. With an effective temperature of 60 700 K and very soft EUV spectrum, this white dwarf resembles the well-studied hot DA white dwarf G 191 − B2B. A follow-up observation made using the *Voyager 2* UV spectrometer reveals a strong continuum shortward of the 912-Å Lyman limit from which we deduce that the neutral hydrogen column density is 1.3×10^{17} atom cm^{-2}.

Key words: stars: atmospheres – stars: individual: RE 0457 − 281 – white dwarfs – ISM: abundances – ultraviolet: stars.

1 INTRODUCTION

Hot DA white dwarfs have for some time been regarded as important probes of the local interstellar medium. Having constant flux and well-modelled spectra, they potentially provide useful 'standard candles' on which the effect of absorption by interstellar material can be measured with observations in the extreme-ultraviolet (EUV) and soft X-ray energy ranges. Although numerous hot white dwarfs have been detected in the 50–250 Å portion of the EUV, relatively few sources have been observed in the longer wavelength end of the EUV band between 500 and 900 Å. At present only three sources, all DA white dwarfs, have been detected in this wavelength band where the absorption cross-section of the interstellar medium (ISM) is at its greatest. The brightest of these three sources, HZ 43 (WD 1314 + 293), was first detected in three photometric bands covering most of the EUV by *Apollo–Soyuz* (Lampton et al. 1976). The first spectrum of HZ 43 in the 500–900 Å band was obtained with *Voyager 2* (Holberg et al. 1980b). A second long-wavelength EUV source, G 191 − B2B (WD 0501 + 527), one of the brightest and hottest catalogued DA white dwarfs, was observed with *Voyager* (Holberg, Forrester & Broadfoot 1980a) shortly thereafter. Recent results from a sounding rocket (Green, Jelinsky & Bowyer 1990) and from the *Hopkins Ultraviolet Telescope* (Kimble et al. 1991) have provided further spectroscopic coverage of G 191 − B2B in this wavelength range. Much fainter long-wavelength EUV emission was also detected with *Voyager* from GD 153 (WD 1254 + 223).

Voyager observations of other catalogued hot DA white dwarfs have revealed no further EUV detections between 500 and 900 Å (Holberg 1991). This is perhaps not surprising, since ISM H I columns greater than a few times 10^{18} cm^{-2} are sufficient to render most sources undetectable in this band. The primary significance, therefore, of the three sources that have been detected lies in the direct observation of the extremely low H I columns, demonstrating the exist-

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ence of at least some 'holes' in the ISM through which other EUV sources might be viewed throughout the EUV wavelength range. Indeed, it is probably not a coincidence that HZ 43 and GD 153 are both observable in the 500–900 Å band, since they are separated by only ≈ 7° on the sky and very likely share a common line of sight through the ISM.

Recently, the *ROSAT* observatory (Trümper 1984) has conducted a survey of the whole sky with two co-aligned telescopes, covering the X-ray and EUV bands. A significant fraction of the EUV sources detected are previously undiscovered hot white dwarfs (Pounds et al. 1993). These provide a pool of new objects which can be observed with *Voyager* to search for low-column directions. We report here the observation of one of these stars which proves to have the lowest column density yet measured.

2 DISCOVERY OBSERVATIONS

One of the hot DA white dwarfs included in our programme of *Voyager* observations was discovered independently by three separate surveys – the EUV all-sky survey of *ROSAT* plus the Montreal–Cambridge–Tololo and Edinburgh–Cape optical surveys of the southern hemisphere. Since the motivation for the *Voyager* observation of this star was its appearance as a very soft source in the *ROSAT* data, we refer to it by the *ROSAT* designation RE 0457 − 281 (RE = *ROSAT* EUV) in the remainder of this paper. The equivalent Montreal–Cambridge–Tololo and Edinburgh–Cape names are MCT 0455 − 2812 and EC 04552 − 2812, respectively. We note here that the appellation derived from the EUV data refers to equinox 2000, whereas the other two refer to equinox 1950. The position, measured directly on the automatic plate measuring machine (APM) plate, is $\alpha_{1950} = 4^{\rm h}\,55^{\rm m}\,13^{\rm s}.97$, $\delta_{1950} = -28°\,12'\,25''.3$. A finding chart is shown in Fig. 1.

The *ROSAT* all-sky survey was conducted by two co-aligned instruments, an X-ray telescope (Pfefferman et al. 1986) and an EUV telescope, the Wide Field Camera (WFC, Wells et al. 1990). The WFC has a 5° field of view and covers a total energy range 0.02–0.2 keV. Its detector has no intrinsic energy resolution, but several bandpasses are defined by thin-film filters analogous to, for example, *UBV* bands in optical photometry. The EUV survey observations were made in only two of the available 'colours' denoted S1 and S2, covering energy ranges (10 per cent of peak effective area) of 90–200 eV (60–140 Å) and 60–110 eV (112–200 Å). Two additional filters are available for the pointed phase of the mission, extending the coverage to lower energies – P1 spans 56–83 eV (150–220 Å) and P2 17–24 eV (500–730 Å). During each *ROSAT* orbit, the survey was conducted by scanning a great circle on the sky on a path passing through the ecliptic poles. The two values of ecliptic longitude scanned at any given time drifted by ≈ 1° per day in order to maintain alignment of the solar panels with the Sun. In this fashion the whole sky was covered in 6 months. Image data for a given area of sky were divided into 2° × 2° 'smallmaps' once the full survey exposure had been achieved. Each smallmap was background-subtracted and searched for significant point sources. The techniques used and criteria for a valid detection are discussed in more detail in the first EUV sky survey catalogue, containing 384 sources (Pounds et al. 1993).

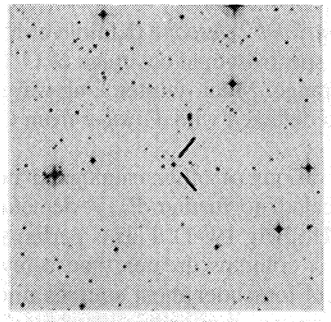

Figure 1. Finding chart for RE 0457 − 281 = MCT 0455 − 2812 = EC 04552 − 2812, reproduced from the ESO Sky Survey J film. North is up and east is left. The field is 15 × 15 arcmin^2.

Cross-correlation of the EUV catalogue with a number of other astronomical catalogues shows that many sources have known counterparts. However, RE 0457 − 281, which is among the brightest EUV sources, was unidentified. An extensive optical observing programme has been conducted to determine the nature of all the unidentified EUV sources. For the southern hemisphere the source positions were compared with lists of objects in the Edinburgh–Cape (EC) survey to select likely counterparts for spectroscopic follow-up. The EC survey is a collaboration between astronomers at the Royal Observatory Edinburgh (ROE) and astronomers from Cape Town, at the South African Astronomical Observatory (SAAO) and the University of Cape Town (UCT). Wide-angle photographs in *U* (UG1 filter with IIa0 emulsion) and *B* (GG385 filter with IIa0) obtained with the UK Schmidt Telescope at Siding Spring are scanned using the ROE COSMOS machine. Blue stellar objects (with $B < 16.5$) are then selected, using the digitized colour information, for further study with photometric and spectroscopic observations made at the Sutherland Station of the SAAO. The survey aims to find all blue objects with $B < 18$ in the region $b > |30°|$ and Dec. < 0°, while classifying all such objects brighter than $B \approx 16.5$. Following the identification at SAAO in 1990 December, follow-up *UVB* and high-speed white light photometry was undertaken with the 1.0-m telescope on 1991 February 18–19. The former observations yielded $V = 13.951 \pm 0.009$, $B - V = -0.321 \pm 0.011$ and $U - B = -1.169 \pm 0.009$. No variability was detected in the high-speed photometry (5-s integrations) during an observation time of 0.72 h.

Independently of the *ROSAT*-related work, another Schmidt survey has been conducted using the CTIO telescope in a collaboration led by the Université de Montréal and Cambridge University (see Demers et al. 1986). In this work, doubly exposed *U* and *B* plates, obtained in 1985, were digitized using the APM machine housed at Cambridge University. The calibrated photographic magnitude of MCT 0455 − 2812 ($B_{\rm pg} = 13.91$) and colour [$(U - B) = -1.28$] made it an outstanding candidate for follow-up spectroscopic observations, which were first obtained on the night of 1986 November 12–13 at the 1.5-m CTIO telescope, and which showed this object to be a hot white dwarf. A spectrum with improved signal-to-noise ratio was obtained more recently (1992 March 24–25) at the Kitt Peak National Observatory 2.1-m telescope, with a Ford CCD detector and at a resolution of ≈ 12 Å. That spectrum is displayed in

Fig. 2, together with that of the well-known hot DA star G 191 − B2B. Detailed fitting of synthetic Balmer line profiles, generated by model atmosphere calculations, to the spectra yield a temperature of 60 700 K (± 1450 K) and a surface gravity of log g = 7.78 (± 0.085) for the white dwarf. This fit is shown in Fig. 3. Furthermore, in the course of follow-up observation of interesting objects within the MCT survey, MCT 0455 − 2812 was also observed with *IUE* on two occasions: first in 1987 September (SWP31698, LWP11560), and again in 1988 November (SWP34704, LWP14406). Both sets of images were obtained through the large aperture, in the low-dispersion mode. As part of the same follow-up programme, Strömgren system colours were obtained as well, and this object was observed at the CTIO 1.0-m telescope on the night of 1988 September 14–15. Our single observation of this object yields y = 13.989, $(b-y) = -0.165$, $(u-b) = -0.304$.

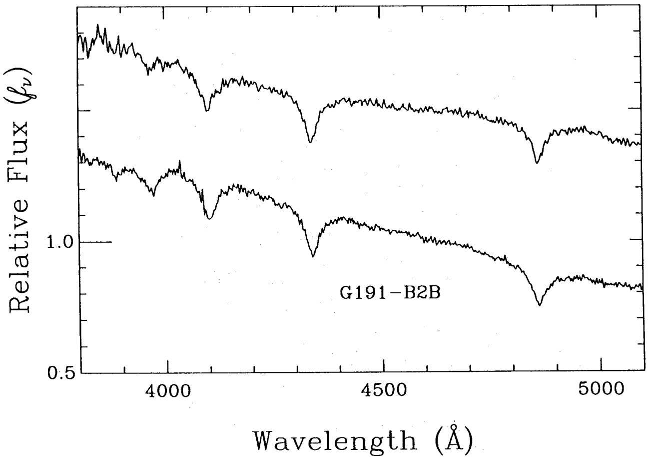

Figure 2. Blue optical spectrum of RE 0457 − 281 (top) with G 191 − B2B shown for comparison. The H Balmer lines from β through to ε can be clearly seen.

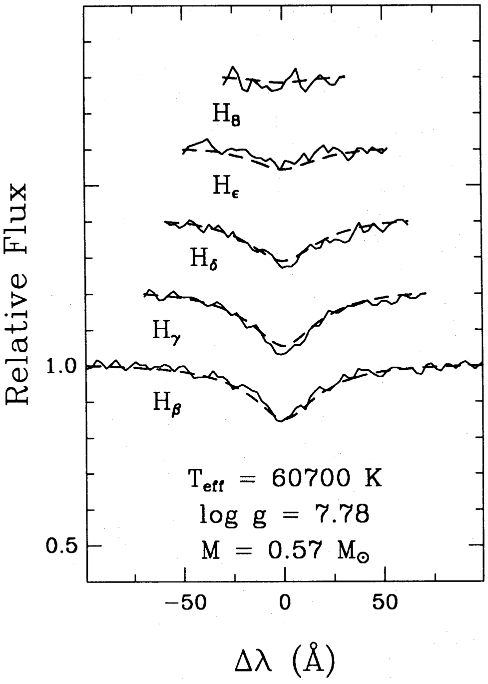

Figure 3. Best fit of synthetic Balmer line profiles to the observed profiles of RE 0457 − 281, yielding T = 60 700 K and log g = 7.78.

3 COMPARISON OF RE 0457 − 281 WITH G 191 − B2B AND HZ 43

Spectroscopic evidence for trace metals has been apparent in many DAs for some time (Bruhweiler & Kondo 1981, 1983). Although, until quite recently, the soft X-ray and EUV opacity exhibited by many hot DA white dwarfs has been almost exclusively interpreted in terms of trace amounts of photospheric He, Vennes et al. (1989) first showed that the puzzling *EXOSAT* spectrum of the hot DA star Feige 24 could best be accounted for by considering the absorption of a host of heavy elements in the photosphere. New results have now decisively focused attention on trace metals as the primary source of this opacity (e.g. Vennes 1992). A detailed analysis of *ROSAT* survey data for a sample of well-studied white dwarfs has demonstrated that above 50 000 K most DA white dwarfs show significant photospheric opacity which cannot be accounted for by H and He exclusively (Barstow et al. 1992, 1993a,b). To this can be added the unique rocket spectrum of G 191 − B2B (Wilkinson, Green & Cash 1992), in which O III and Fe VI are tentatively identified as dominating the 200–330 Å spectral region.

In the Barstow et al. (1993b) study, EUV opacity extremes are represented by HZ 43 (50 000 K), which has no additional opacity source, and G 191 − B2B (57 500 K), where the effect is large. These results were obtained by comparing the observed EUV count rates with the predictions of model atmosphere calculations comprising H and He only, both as a homogeneous mixture and in a stratified configuration. A χ^2 statistic was then calculated to determine the quality of agreement between data and predictions, taking into account the uncertainties in the measured count rates and instrumental calibration. We have repeated the same analysis on RE 0457 − 281, utilizing the S1 and S2 count rates (see Table 1) and observed H I column (see Section 4), and taking into account the optically determined temperature and surface gravity. Within the temperature range allowed by the optical data, it is not possible to find an acceptable fit for either a homogeneous or a stratified H + He atmosphere. Consequently, it is clear that RE 0457 − 281 must also contain trace metals in its atmosphere to account for the required opacity, in keeping with the majority of DA white dwarfs that have been studied in this temperature regime.

Table 1. Observed EUV count rates for RE 0457 − 281, HZ 43 and G 191 − B2B and values normalized relative to the V magnitude of HZ 43.

	HZ 43	RE 0457 − 281	G 191 − B2B
Temp (K)	50 000	60 700	57 400
m_V	12.99	13.99	11.80
S2 rate (count s^{-1})	42.0	2.54	2.8
S1 rate (count s^{-1})	14.9	0.11	0.06
Normalization factor	1	2.5	0.13
S2 normalized rate	42.0	6.4	0.36
S1 normalized rate	14.9	0.28	0.008

Further interpretation of the data is restricted by the fact that photometric data of the kind provided by *ROSAT* will never be able to determine unambiguously the nature and abundance of the opacity sources. These can only be found by spectroscopic observations. Nevertheless, we can study the emergent EUV fluxes for RE 0457 − 281 and compare it with HZ 43 and G 191 − B2B. Since these objects do not lie at equal distance, a comparison of their absolute EUV fluxes is only possible if the observed count rates are re-normalized to their V magnitudes (y for RE 0457 − 281). Table 1 summarizes both the observed S1 and S2 count rates and the values scaled to the V magnitude of HZ 43. RE 0457 − 281 is rather hotter than HZ 43 but is clearly less luminous in the EUV, demonstrating that photospheric opacity is required beyond that provided by a nearly pure H atmosphere. Conversely, RE 0457 − 281 is brighter than the slightly cooler white dwarf G 191 − B2B. Although on first appearances G 191 − B2B and RE 0457 − 281 are similar objects, there are obvious differences in the amount of photospheric absorbing material present. The presence of trace metals in DA white dwarf atmospheres is probably the result of radiative levitation countering the downward force of gravity (e.g. Chayer, Fontaine & Wesemael 1989, 1991). Observed abundances will be determined by the temperature and gravity of an individual star. Greater abundances are expected for higher temperatures. Over the temperature range spanned by G 191 − B2B and RE 0457 − 281, the hotter star should then have the greater EUV opacity and, therefore, the lower EUV flux. We see the reverse. The surface gravity of RE 0457 − 281 is somewhat higher ($\log g = 7.78$) than G 191 − B2B ($\log g = 7.5$). It is possible that the lower photospheric opacity apparent in RE 0457 − 281 is a result of the higher gravity countering the radiation pressure more effectively, an effect that appears to be evident in the larger sample of hot DAs studied in the *ROSAT* survey (Barstow et al. 1993b). The observed difference in gravity may not be significant, however, because of the uncertainties in determining $\log g$ for each star, and a firm conclusion cannot be drawn.

4 *VOYAGER* OBSERVATIONS

Voyager observations of RE 0457 − 281 were obtained over a 3-d period between 1991 September 6 and 9 with the *Voyager 2* spacecraft (Holberg 1990). Adjacent sky background spectra were also obtained from a position approximately 1°.5 to the south of the star. The location of this sky background observation closely coincided with the position of a faint DAB white dwarf also discovered as part of the MCT survey. Careful reductions of the background observation reveal no evidence for the presence of this star and no FUV or EUV emission above the sky background levels. Consequently, we have used this sky background to reduce our observation. RE 0457 − 281 was well centred with respect to the spacecraft limit cycle motion, and standard reduction procedures were used to extract a spectrum having an effective integration time of 14 000 s. In Fig. 4 we show the observed count-rate spectrum compared with that of a recent *Voyager 2* spectrum of HZ 43, a DA white dwarf similar in effective temperature, and the brightest known EUV source in the 500–900 Å band (Holberg, private communication). In spite of the fact that HZ 43 is approximately 80 per cent brighter in the FUV, the two stars have nearly matching 500–900 Å EUV fluxes, clearly indicating that RE 0457 − 281 has a lower H I column density than that of HZ 43.

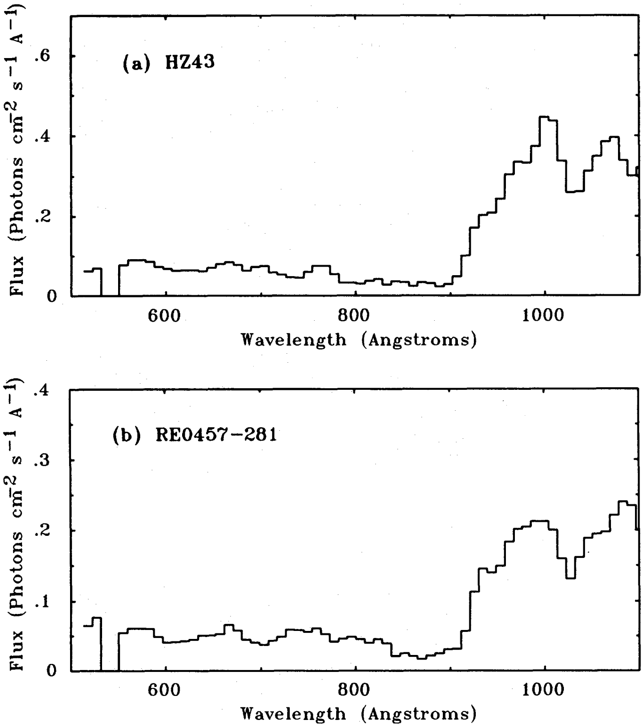

Figure 4. *Voyager 2* spectrum of RE 0457 − 281 (b) compared with a recent *Voyager 2* observation of the prototype EUV source HZ 43. Significant flux, indicative of an extremely low line-of-sight interstellar H I density, is evident.

In Fig. 5 we show a composite *Voyager–IUE* SWP energy distribution of RE 0457 − 281 covering the region 500–2000 Å. The *Voyager* RE 0457 − 281 fluxes in this plot are truncated for wavelengths longward of 1130 Å due to heavy subtraction of the intense H I Lyman alpha sky line from the interplanetary medium and low stellar count rate at these wavelengths. Also shown is a best-fitting model atmosphere energy distribution. The model used here is a pure H blanketed model like the model grid used to analyse the Balmer profiles. An effective temperature of 59 950 K, which is consistent with the optical temperature determination, and an H I column density of $(1.3 \pm 0.7) \times 10^{17}$ cm^{-2} are determined from these data. We note that there is a ≈ 10 per cent offset between the absolute flux levels of the *IUE* and *Voyager* data when compared with the model spectrum. This is within the estimated uncertainty in the absolute calibration of the *Voyager* UVS, which is discussed in Holberg et al. (1991).

5 DISCUSSION

The galactic coordinates of the RE 0457 − 281 field ($l = 229°.3$, $b = -36°.2$) place it well within the low-density 'fourth quadrant' ($l = 200°–270°$) reported by Paresce (1984) in his study of the distribution of interstellar material. It is perhaps not surprising that this particular viewing direction has a low column density. The result we obtain here, how-

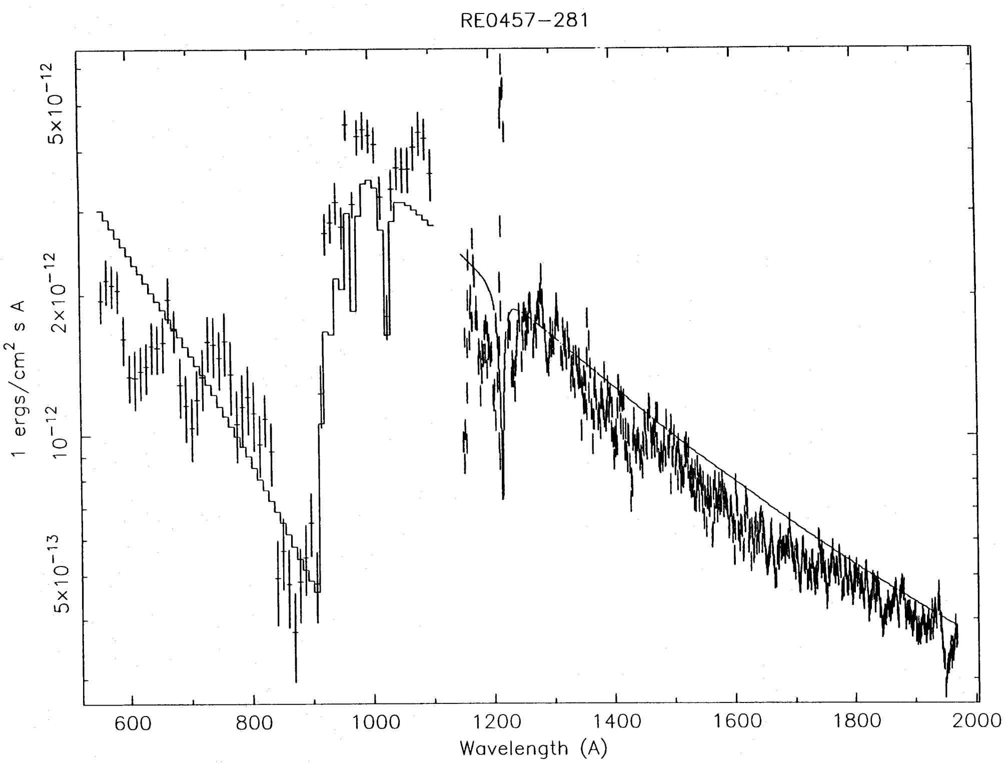

Figure 5. Composite *Voyager* and *IUE* SWP spectra of RE 0457 − 281. The solid curve shows the best-fitting model spectrum with log *g* fixed at 7.78. *T* and N_H were allowed to vary freely, yielding values of 59 950 K and 1.3×10^{17} cm^{-2}, respectively. The sharp peak at 1216 Å is geocoronal Lyman alpha emission which fills in the photospheric absorption profile. The relative offset in absolute flux between the *Voyager* and *IUE* data, when compared with the model, is within the estimated uncertainty in the absolute calibration, which is not accounted for in the error bars.

ever, is remarkable in that, to our knowledge, this is the lowest direct measurement of H I column reported anywhere in the literature. From its *V* magnitude and temperature we estimate that the distance to the star is about 90 pc, on the assumption that its radius is typical of most white dwarfs. Our column density measurement then translates into an average volume density of 0.0005 atom cm^{-3}. This is two orders of magnitude below the local average of 0.007 atom cm^{-3} and, if a true representation of the amount of material present, is similar to gas densities found in intergalactic space.

We must ask the question as to how such a low-density region of H I might arise. One hypothesis is that an ancient supernova event some 2×10^7 yr ago formed a gas-free cavity, the 'local bubble', in which the Sun now resides (Cox & Reynolds 1987). It has also been proposed by Gehrels & Chen (1993) that a much more recent event may have been responsible for the 'local bubble'. They hypothesize that the well-known gamma-ray source Geminga resulted from a Type II supernova which occurred approximately 3×10^5 yr ago. Using the measured proper motion of Geminga, Gehrels & Chen (1993) arrived at a location for the supernova event in the direction of $l = 197°$ and $b = -11.°7$ and within a distance of 60 pc from the Sun. Although RE 0457 is some 27° from this location, it is interesting to note that two other EUV sources which are also bright at 500 Å, and longer, occur along lines of sight near the postulated Geminga event: G 191 − B2B ($l = 156.°3$, $b = 7.°6$, $d = 44$ pc) and ε CMa ($l = 239.°8$, $b = -11.°3$, $d = 188$ pc). The latter is in fact reported to be the brightest EUV source in the sky at long wavelengths (Vallerga 1992). Together, these three sources define a region ≈ 0.3 sr in extent, centred on the location of the postulated Geminga event. The fact that all these sources are detectable at wavelengths longer than 500 Å implies the existence of an extended cavity-like region of low H I density. According to Chevalier (1974) a typical supernova event of energy ≈ 10^{51} erg could produce a cavity of ≈ 100-pc diameter. RE 0457 − 281 is just close enough to lie in the same bubble as the Sun. There is further evidence to support this idea from radio scintillation data (Hajivassilliou 1992), where the pattern of turbulence is modelled with a local supernova remnant bubble which lies in the direction of the RE 0457 − 281 field.

An alternative way to account for the low column density of neutral hydrogen would be the involvement of a significant photoionization of the gas by RE 0457 − 281 and an unusual group of three other white dwarfs that are within a radius of 1° on the sky. However, the time required to ionize the volume envisioned here is likely to be longer than the age of all but the coolest white dwarf of the group. At most, this group of hot stars could have helped prevent significant recombination of previously photoionized gas over the past ≈ 2×10^6 yr. All in all, it seems to us more likely that the region is substantially devoid of any material.

Welsh (1991) reports the existence of a tunnel of neutral gas in the direction of β CMa and draws a similar conclusion about the likely density of any ionized material. Lying at a longitude ($l = 235°$) near to that of RE 0457 − 281, the tunnel is closer to the galactic plane ($b = -15°$). Extending at least 10°–15° on the sky, it could be as large as 30° across

(Welsh et al. 1991). It is tempting to suggest that the RE 0457 − 281 region could be a further southward (in galactic coordinates) extension of the β CMa low-density tunnel, although we note that there is no direct evidence in support of this as yet.

6 CONCLUSIONS

With three independent sky surveys, covering the EUV and optical bands, we have discovered a new hot DA white dwarf. The star is similar to G 191 − B2B in requiring additional photospheric opacity sources, when compared with the pure H composition of HZ 43, to explain the emergent EUV flux. It is also clear, however, that there is less absorbing material in RE 0457 − 281, despite the higher temperature (by ≈ 4000 K). A *Voyager* UVS observation shows that the line-of-sight H I column density is 1.3×10^{17} cm^{-2}, yielding an average volume density of 0.0005 atom cm^{-3} over the stellar distance of 90 pc. A search of the available literature shows that these are the lowest direct measurements of H I density yet reported. It is probable that the region is also devoid of any ionized material like the β CMa tunnel. We suggest that the RE 0457 − 281 void could be a southernward extension of the tunnel, but further observations will be required to confirm this.

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