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ON THE PREDICTED ABUNDANCES OF IRON AND NICKEL SUPPORTED BY RADIATIVE LEVITATION IN THE ATMOSPHERES OF HOT DA WHITE DWARFS

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ABSTRACT

We present the results of detailed radiative forces calculations for iron and nickel levitating in hot DA white dwarf atmospheres. This follows from the determination of the iron abundance in a handful of hot DA stars by a number of authors and, more particularly, from the recent identification and abundance analysis of nickel carried out by Werner & Dreizler for these same stars. Our calculations are based on the extensive atomic data set compiled by Kurucz for the iron group elements. We show that radiative levitation is more than sufficient to account for the abundances of iron and nickel observed in hot DA white dwarfs. However, we also find that the observations exhibit an abundance pattern which cannot be explained in detail by the predictions of radiative levitation theory. This finding adds to mounting evidence that other mechanisms must be at work in the atmospheres of these objects and compete with radiative levitation and gravitational settling.

Subject headings: atomic processes — stars: abundances — white dwarfs

1. INTRODUCTION

Over the last several years, considerable interest has developed in the unusual atmospheric composition of white dwarf stars. This was made possible largely through the opening of new spectral windows provided by space-borne observatories such as the *International Ultraviolet Explorer*, *Einstein*, *EXOSAT*, *ROSAT*, the *Extreme Ultraviolet Explorer*, and the *Hubble Space Telescope*. With a few notable exceptions, it appears that the photospheric layers of hot white dwarfs in particular are generally polluted by traces of heavy elements in nonsolar proportions. There exists a wide consensus that selective radiative forces must play a key role in this contamination phenomenon. And, indeed, the exploratory calculations of Vauclair, Vauclair, & Greenstein (1979; see also Fontaine & Michaud 1979) have demonstrated that traces of C, N, and O can levitate through bound-bound absorption in the relatively strong radiation field found in hot white dwarf atmospheres.

In order to test properly the theory of radiative levitation in these stars, it is necessary to make quantitative comparisons of observed and predicted abundances. Unfortunately, accurate determinations of the observed abundances through model atmosphere and spectral synthesis techniques have remained quite scarce. Currently, abundances of C, N, Si, and Fe have been determined in only a handful of hot DA white dwarfs (Wesemael, Henry, & Shipman 1984; Vennes, Thejll, & Shipman 1991; Vennes et al. 1992; Holberg et al. 1993; Vidal-Madjar et al. 1994). Useful upper limits on the abundances of C, N, and Si have also been derived by Vennes, Thejll, & Shipman (1991) for another dozen DA stars. In addition, abundances or upper limits for He in hot DA and DAO stars have been obtained by Bergeron et al. (1993, 1994; see also Napiwotzki et al. 1993). Finally, similar analyses have been carried out for only two hot helium-rich (DO) white dwarfs (Sion, Liebert, & Wesemael 1985; Werner, Heber, & Fleming 1994), and abundances have been determined for C, N, and O in these stars.

In this context, the recent paper of Werner & Dreizler (1994, hereafter WD94) is of considerable importance. These authors have succeeded in identifying Ni features for the first time in the (ultraviolet) spectra of white dwarfs. Their quantitative analysis has led to the determination of Ni abundances in the four hot DA white dwarfs G191−B2B, Feige 24, RE 0623−377, and RE 2214−492. Not surprisingly perhaps, and because of their relative brightnesses and rich spectra, these stars already constituted the best-studied cases for abundance determinations of C, N, Si, and Fe by previous authors (WD94 provide also new estimates for the Fe abundances). The addition of nickel to a short list of only four elements is particularly important because the *relative* abundances of various pollutants in the atmosphere of a given star hold essential information as to the true role of radiative levitation. Furthermore, iron group elements can provide substantial EUV opacity and hold a key role in our understanding of EUV spectra of hot white dwarfs (see, e.g., Vennes et al. 1989, 1992).

We recently completed a detailed investigation of radiative forces calculations for several astrophysically important elements in hot white dwarfs (for both DA and non-DA stars; Chayer, Fontaine, & Wesemael 1994; hereafter referred as CFW94). In this effort we used the extensive and homogeneous data bank TOPBASE (Cunto & Mendoza 1992) associated to the Opacity Project (Seaton et al. 1992) in order to obtain the *gf*-values needed for computing radiative accelerations through spectral lines. The heaviest element included in TOPBASE is iron, which implies that, unfortunately, no information about the radiative levitation of nickel was derived. In view of the significance of the findings of WD94, however, we decided to carry out additional computations to investigate the potential of radiative support on nickel in hot DA atmo-

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spheres. The main goal of this *Letter* is to summarize the results of these calculations. In addition, we take this opportunity to upgrade our computations of radiative forces on iron in order to compare with the determinations of WD94, in particular with their determination of the Fe/Ni ratio in their four target stars.

2. COMPUTATIONS

Our approach to the computation of radiative forces and equilibrium abundances is similar to that briefly summarized in Chayer, Fontaine, & Wesemael (1991), where we presented our first results on iron. Since then, our ability to model more realistically the mechanism of radiative levitation in white dwarfs has increased dramatically, thanks to the availability of large atomic data bases such as TOPBASE (Cunto & Mendoza 1992) and the most recent compilations of Kurucz (1991, 1992). It is now possible to include in the calculations a much larger number of transitions with reliable *gf*-values than before. As an example, the calculations presented in Chayer, Fontaine, & Wesemael (1991) included 3786 transitions with oscillator strengths either taken from Fuhr et al. (1981) or estimated from the approximate prescription of Michaud et al. (1976) when not available from Fuhr et al. The calculations presented by Vennes et al. (1992) were based on the same approach. Our most recent survey in this area (CFW94) includes results for iron which incorporate all the 392,412 transitions of Fe III through Fe XXVI with $gf \geq 10^{-3}$ and $\lambda \leq 10^4$ Å available in TOPBASE.

For our investigation of the radiative support on Ni, we turned to the extensive data set of Kurucz (1991, 1992) which, among other things, provides *gf*-values for iron group elements in their first nine ionization states. We incorporated all 4,050, 204 transitions with $gf \geq 10^{-3}$ listed in the Kurucz tables for Ni I through Ni IX. Tests indicate that weaker lines ($gf \leq 10^{-3}$) do not contribute significantly to the radiative support. In order to provide a meaningful comparison with the Fe/Ni value obtained by WD94 in their analysis, we also considered the iron data in the Kurucz databank. All available 2,778,798 transitions with $gf \geq 10^{-3}$ for Fe I through Fe IX were included in the calculations. The energy levels for Ni were taken from the compilations of Corliss & Sugar (1981), and those for Fe were taken from TOPBASE. For the line shape, we used a Voigt profile which incorporates the radiative and Stark broadening parameters given by Kurucz.

We computed representative atmospheric abundances of iron and nickel at the Rosseland photosphere ($\tau = \frac{2}{3}$) of gray model atmospheres assuming a strict equilibrium between the effective gravity and the radiative acceleration. The model atmospheres/envelopes have a pure hydrogen composition and are computed on a grid with four values of the gravity log g = 7.0, 7.5, 8.0, 8.5, and 17 values of the effective temperature in the range 20,000 K $\leq T_{\rm eff} \leq$ 100,000 K in steps of 5,000 K. In this range of atmospheric parameters, the ionization states of importance are Fe III through Fe VII and Ni II through Ni VII, which are well covered by both the Kurucz and TOPBASE data sets (only Fe in the latter case). More details about the stellar models used as well as a discussion of the basic hypotheses and limitations of our current approach to radiative forces calculations may be found in CFW94.

3. RESULTS AND DISCUSSION

Our calculations are summarized in Figure 1 where we show for both iron (upper panel) and nickel (lower panel) the expected number abundance ratio with respect to hydrogen as a function of effective temperature. Each solid curve corresponds to a fixed surface gravity with, from top to bottom, log g = 7.0, 7.5, 8.0, and 8.5. Each curve begins at the coolest effective temperature of our grid for which radiative support is possible. Thus, and for example, some nickel is radiatively supported for $T_{\rm eff} \geq$ 25,000, 35,000, 40,000, and 50,000 K in our models with log g = 7.0, 7.5, 8.0, and 8.5, respectively. The horizontal dashed curves refer to the solar values as given by Grevesse & Noels (1993) for Fe, and by Anders & Grevesse (1989) for Ni. The expected Fe and Ni atmospheric abundances increase monotonically with increasing effective temperature and decreasing surface gravity. We note that for the higher effective temperatures, substantial overabundances of Fe and Ni are predicted (as compared to solar values), even for the largest surface gravity (log g = 8.5) considered here. This is particularly true for nickel whose cosmic abundance is some 18 times smaller than that of iron. Such large overabundances can easily materialize in the atmospheric regions because reservoirs of Fe and Ni supported by radiative levitation extend quite deep in our stellar envelopes.

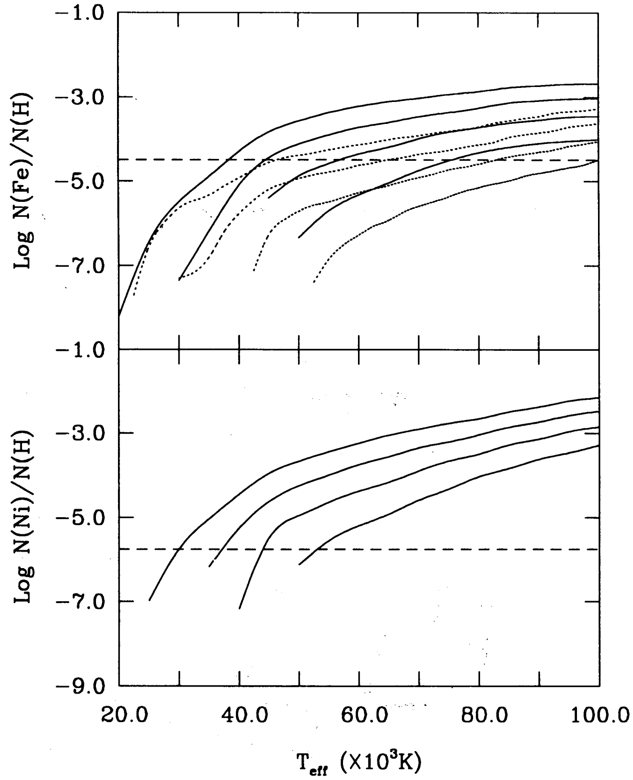

FIG. 1.—Predicted abundance supported by radiative levitation as a function of effective temperature (*upper panel*; iron *lower panel*: nickel). The solid curves correspond to the computations based on the Kurucz data set and refer to models with a fixed surface gravity with log g = 7.0, 7.5, 8.0, and 8.5, from top to bottom. The dotted curves in the upper panel are similar but correspond to the calculations which use TOPBASE. The dashed horizontal lines indicate the solar values of the abundances, Fe/H = 3.24×10^{-5} and Ni/H = 1.78×10^{-6}.

For the reasons given in WD94, namely, that the iron group elements have comparable ionization potentials and similar atomic structures, one might expect a priori that the equilibrium abundances of these elements supported by radiative levitation in a given star should also be comparable. This is indeed what our results indicate at lower effective tem-

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peratures, except that there is a noticeable difference for $T_{\rm eff} \gtrsim 70{,}000$ K in the sense that the predicted abundance of nickel becomes systematically larger than that of iron for given $T_{\rm eff}$ and log g. In the range 70,000 K $\lesssim T_{\rm eff} \lesssim$ 100,000 K, the ionization states of importance for radiative support are Ni VI and Ni VII (Fe VI and Fe VII). For these two ionization states, the Kurucz tables list about 5 times more transitions for nickel than iron, so it is perhaps not surprising that the radiative support on nickel is enhanced in this range of effective temperature. In this connection, we stress the fact that the present calculations are based on the implicit assumption that a given element (either iron or nickel) levitates under the influence of the radiative flux provided by a *pure* hydrogen atmosphere. In other words, the blocking effect due to the opacity of the trace element (as well as *others*) is not taken into account in our calculations. This blocking effect could potentially be very important and reduce considerably the abundances supported by radiative levitation, especially through the influence of the iron group elements which show relatively large opacities. This is further discussed below.

In the upper panel of Figure 1, we have also reported our previous results (CFW94) for iron (the dotted curves) obtained through the use of the TOPBASE data set. These earlier calculations were carried out on a finer grid of effective temperature with $\Delta T_{\rm eff} = 2{,}500$ K. A comparison indicates that, on the average, the predicted Fe abundance in the present investigation is about 8 times larger than the abundance obtained by CFW94. In large part this must be due to the fact that a significantly larger number of transitions (approximately 7 times more) were available in the Kurucz data set as compared to TOPBASE. This difference is caused by the inclusion of the fine structure in the Kurucz database, which is ignored in TOPBASE. We have verified explicitly that the weaker components of a multiplet saturate at larger abundances than the average transition, thus providing more radiative support at a given abundance. However, the difference must also reflect intrinsic differences in the physics on which the two data sets are based. Hence, to a certain extent, the comparison discussed here typifies the actual accuracy with which we can compute radiative forces on iron group elements in white dwarfs on the basis of the largest atomic data sets currently available.

In a format similar to that used by WD94, Table 1 contrasts the observed (WD94) abundances of iron and nickel with those predicted by radiative levitation theory on the basis of the Kurucz (K) and TOPBASE (T) data sets for the four DA white dwarfs discussed by these authors. The predicted abundances have been obtained by direct interpolation in our grid of models using the atmospheric parameters given by WD94, which we have reported in the second and the third columns of Table 1. The original determinations of the atmospheric parameters are due to Finley et al. (1994) for G191−B2B, Holberg et al. (1986) for Feige 24, and Holberg et al. (1993) for both RE 0263−377 and RE 2214−492. We note that radiative levitation is amply sufficient by itself to account for the iron and nickel abundances observed in those hot DA stars. This is in contrast, for example, to the case of helium whose presence cannot be explained in terms of radiative levitation in the atmospheres of DAO stars because the radiative support is too small (Vennes et al. 1988; Bergeron et al. 1994). This is also in contrast to the findings of Vennes et al. (1992) on iron who, however, correctly pointed out that their treatment of line absorption could have underestimated the abundance supported by radiative levitation. The predicted abundances of iron on the basis of TOPBASE are either consistent with, or slightly higher than the inferred abundances of WD94 for the four stars considered in Table 1. The abundances of both iron and nickel computed on the basis of the Kurucz databank are significantly higher than the observed abundances. We point out that our estimates of the abundances of Fe and Ni supported by radiative levitation could certainly be improved by adapting the method of calculations proposed by Gonzalez et al. (1994), but this would not account for the fact that the two RE objects are more metal-rich than G191−B2B and Feige 24, two stars with similar atmospheric parameters. This trend cannot be explained by the predictions of radiative levitation theory.

We remind the reader that these discrepancies between the observed and predicted abundances should not be too surprising. Indeed, our approach ignores implicitly the potential presence of other mechanisms which may interfere and compete with radiative levitation and gravitational settling. We already concluded some years ago that the simple idea of a strict equilibrium between the radiative acceleration and the local effective gravity is insufficient to explain the observed abundance pattern of heavy elements in hot white dwarfs (Chayer et al. 1987; Chayer, Fontaine, & Wesemael 1989), and the present results certainly strengthen this conclusion. We suggested that the presence of weak stellar winds could be of importance in establishing the atmospheric abundances of heavy elements in hot white dwarfs, and this is currently under investigation (see, e.g., Chayer et al. 1993 for a brief progress report). However, we can think of other processes as well such as turbulence or even accretion which could potentially affect the atmospheric composition. In addition, the blocking effect alluded to above is possibly quite important. Qualitatively, one would expect a reduction of the iron and nickel abundances below the predictions of pure radiative levitation. This goes in the right direction as far as the data of Table 1 are concerned, but the process needs to be investigated quantitatively.

It is interesting, in this connection, to look at the Fe/Ni ratio. In the absence of sources of opacity other than pure hydrogen, and because of the similarity between Fe and Ni emphasized by WD94, the predicted ratio Fe/Ni is of order unity, as given in the last column of Table 1. The ratio inferred

TABLE 1

OBSERVED (WD94) AND PREDICTED (K, T) IRON AND NICKEL ABUNDANCES IN FOUR DA WHITE DWARFS

Star	$T_{\rm eff}$	log g	Fe/H (WD94) (10^{-5})	Fe/H (K) (10^{-5})	Fe/H (T) (10^{-5})	Ni/H (WD94) (10^{-5})	Ni/H (K) (10^{-5})	Fe/Ni (WD94)	Fe/Ni (K)
G191−B2B	60,400	7.54	0.5–1.0	18.2	2.3	~0.1	17.4	5–10	1.05
Feige 24	55,000	7.23	0.8–1.2	28.5	3.7	0.1–1.5	24.0	1.6–12	1.19
RE 0623−377......	60,300	7.34	3–10	32.6	4.0	1–5	31.5	0.6–10	1.03
RE 2214−442......	63,500	7.50	3–10	23.0	2.9	2–8	24.4	0.4–5	0.94

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by WD94 is typically larger than ~ 1 (the value expected in the absence of blocking) and smaller than ~ 18 (a value which presumably reflects the primordial abundances unaltered by radiative levitation). This suggests that, in real stars, iron is somehow more successful than nickel at getting supported by selective radiative forces through their competition for the available photons. It remains to be seen if the blocking effect can explain this competition process. We are currently investigating this possibility in detail and will report our results in due time.

After this manuscript was submitted, we became aware of a recent paper by Holberg et al. (1994) which discusses their independent discovery and abundance analyses of Ni in RE 2214−492 and G191−B2B. The referee also kindly pointed out to us the existence of this important contribution. In RE 2214−492, Holberg et al. (1994) find $Ni/H \simeq 3 \times 10^{-6}$, a value substantially smaller than that derived by WD94 ($Ni/H \simeq 5 \times 10^{-5}$) and outside of the respective formal error ranges. They also provide a new estimate of the iron abundance $Fe/H \simeq 10^{-4}$ which is consistent with, but somewhat larger than, that reported by WD94 ($Fe/H \simeq 6.5 \times 10^{-5}$). This leads to a ratio $Fe/Ni \simeq 32$ which suggests an extreme blocking effect in that star. In the case of G191−B2B, Holberg et al. (1994) find $Ni/H \simeq 10^{-6}$ and $Fe/H \simeq 3 \times 10^{-5}$, which also lead to a ratio $Fe/Ni \simeq 32$. It remains to be seen if such large ratios can be accounted for by theory.

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