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AN EXPLANATION FOR THE PECULIAR EUV SPECTRUM OF THE HOT DA WHITE DWARF FEIGE 24

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ABSTRACT

We present new model atmosphere modeling of the high-resolution EUV spectrum of the hot DA white dwarf Feige 24 measured with *EXOSAT* by Paerels *et al.* The possibility that the measured spectrum originates in a stratified atmosphere, with a thin hydrogen layer in diffusive equilibrium over the helium envelope, is first examined. No stratified model atmosphere can account simultaneously both for the lack of He II edge at 228 Å and the observed steep drop in flux shortward of 250 Å. We then consider the possibility that many different metals could be present in low abundances in the atmosphere of Feige 24, and show that such a model reproduces satisfactorily the observed EUV spectrum. The abundances required to fit the spectrum are roughly consistent with the predictions of radiative element support. The implications of this result for the suggested existence of stratified atmospheres in hot DA stars, and for our understanding of the properties of the thermal EUV and X-ray emission in these objects are briefly discussed.

Subject headings: stars: atmospheres — stars: white dwarfs

I. INTRODUCTION

Feige 24 is a bright DA white dwarf which has been studied extensively from ground-based and space-borne observatories. It was the second extreme-ultraviolet (EUV) source detected (Margon *et al.* 1976), and the ultraviolet tail of its photospheric spectrum has since been the subject of several additional studies (Holm 1976; Wesselius and Koester 1978; Cash, Bowyer, and Lampton 1979; Holberg 1984; Holberg, Wesemael, and Basile 1986). At the same time, optical spectrophotometry reveals the presence of a red companion (Oke 1974), which also shows up in the optical spectrum (Eggen and Greenstein 1965). Liebert and Margon (1977) assign to the secondary a spectral type M1–2 V, while Thorstensen *et al.* (1978) reported a period of $4^{\mathrm{d}}.23$ and a significant reflexion effect in the system. Interestingly, the primary is one of only a handful of DA stars which exhibit narrow photospheric metal lines in their ultraviolet spectrum (Dupree and Raymond 1982). The C, N, and Si abundances determined for this object remain well below solar (Wesemael, Henry, and Shipman 1984) and the most plausible explanation to account for their presence is the influence of selective radiative forces (Morvan, Vauclair, and Vauclair 1986; Chayer *et al.* 1987), possibly coupled to a weak wind (Chayer, Fontaine, and Wesemael 1988).

Interest in Feige 24 was revived by the recent *EXOSAT* observations of that star (Paerels *et al.* 1986). Feige 24 was already known to be a strong EUV source from Apollo-Soyuz photometry (Margon *et al.* 1976), but *EXOSAT* revealed an unexpected spectrum in that wavelength range. It consist of an essentially featureless continuum which shows a maximum around 250 Å and a steep drop at shorter wavelengths; it can be nominally fitted with a blackbody energy distribution with $T = 31{,}000$ K, assuming an interstellar neutral hydrogen column density of $n_{\mathrm{H}} = 1.2 \times 10^{19}$ cm^2 (Parels *et al.* 1986). Most notably, however, the spectrum looks strikingly different from those of HZ 43 and Sirius B, the only two other objects observed with the Transmission Grating Spectrometer (Paerels and Heise 1988). So puzzling is the EUV spectrum that early discussions of the data included the possibility that the primary not be a white dwarf at all, but rather a hot subdwarf (e.g., Heise 1985), despite evidence based on the spectrophotometric and spectroscopic parallaxes (Holm 1976; Liebert and Margon 1977). The latest analysis of Paerels *et al.* (1986) now allows them to rule out a white dwarf atmosphere in LTE with (1) a pure hydrogen composition; (2) a hydrogen-dominated composition with uniform traces of helium; and (3) a hydrogen-dominated composition with small uniform traces of C, N, Si at the levels determined by Wesemael, Henry, and Shipman (1984). Paerels *et al.* (1986) conclude by pointing out the need for more sophisticated model atmospheres including, in particular, chemical stratification and NLTE effects.

In an independent investigation, we have been led to the suggestion that the need for a soft X-ray opacity in hot DA stars could perhaps best be accounted for if a majority of those stars have layered atmospheres with a thin hydrogen layer in diffusive equilibrium over a helium envelope (Vennes *et al.* 1988). As a natural follow-up to this idea, we have computed a grid of such stratified model atmospheres (Vennes, Fontaine, and Wesemael 1988). The question that arises is whether or not such a stratification could account for the EUV spectrum of Feige 24. The basic idea here is that the hydrogen layer must be sufficiently thick that a pure hydrogen spectrum is formed in the optical region and, yet, sufficiently thin that the EUV flux escaping from deeper layers is regulated by the opacity of helium in these regions. Our calculations presented in § II show that, in contrast to the suggestion of Paerels *et al.* (1986) and our own optimistic assessment (Vennes *et al.* 1988), the EUV spectrum of Feige 24 *cannot* be explained in terms of a H/He stratified atmosphere, and that other explanations of the peculiar EUV spectrum must be considered. In § III, we consider one such alternative and show that it represents a viable explanation for the puzzling spectral shape observed from *EXOSAT*.

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II. FEIGE 24: A STRATIFIED ATMOSPHERE?

As part of an investigation of the atmospheric properties of hot DA stars (e.g., Vennes, Fontaine, and Wesemael 1988), we have calculated several stratified model atmospheres with parameters sufficiently close to those of Feige 24 for us to investigate this alternative. Our computational method is quite similar to that used by Jordan and Koester (1986), in that the transition region is treated self-consistently through the use of the equilibrium composition gradient. This is in contrast to earlier investigations which used a discontinuous transition between the hydrogen-rich and helium-rich layers. While details will be given elsewhere, it is appropriate to point out that our stratified models yield hydrogen layer masses for the stars observed by *EXOSAT* (Vennes, Fontaine, and Wesemael 1988) which are in excellent agreement with those determined independently by Koester (1988).

Two such models are shown in Figure 1 (*top*), together with the *EXOSAT* Al/P filter data, taken from Paerels *et al.* (1986). The models shown have $T_e = 50{,}000$ K, log $g = 8.0$; the fit to the Lyα data of Holberg, Wesemael, and Basile (1986) yields, on the other hand, $T_e = 55{,}000 \pm 5400$ K and log $g = 7.23 \pm 0.35$. These differences in adopted parameters are not likely to affect the conclusions derived here. The theoretical spectra in Figure 1 (*top*) were first scaled to match the observed V magnitude ($v = 12.56$), attenuated with a neutral hydrogen column density of 3.5×10^{18} cm^2, transformed to count rate spectra, and finally degraded to a spectral resolution of 6 Å. The cases shown are for a varying hydrogen layer mass. The first one has a hydrogen layer so thick [log $\Delta M(\mathrm{H})/M = -14$] that the EUV spectrum is practically the same as that of a homogeneous pure H model; the second one has a thinner hydrogen layer [log $\Delta M(\mathrm{H})/M = -15$] which allows helium to pollute the EUV photosphere and reduce considerably the flux at short wavelengths. The fit is clearly unsatisfactory, and this for fundamentally the same reasons which led Paerels *et al.* to reject the homogeneous H/He atmosphere model: if the hydrogen layer is sufficiently thin for helium to be abundant enough to quench the short-wavelength flux, it also leaves an obvious signature, namely an absorption edge at 228 Å which is not observed in this object. Indeed, the lack of He II edge is particularly inconsistent with the drop in flux below 250 Å. Stratified models which pass the stringent constraint imposed by the lack of edge predict steeply *rising* fluxes below 250 Å, in sharp contrast to the observed spectrum. There seems to be no reasonable way to escape this contradiction, and the option of a stratified atmosphere for Feige 24 should, in all probability, be laid to rest.

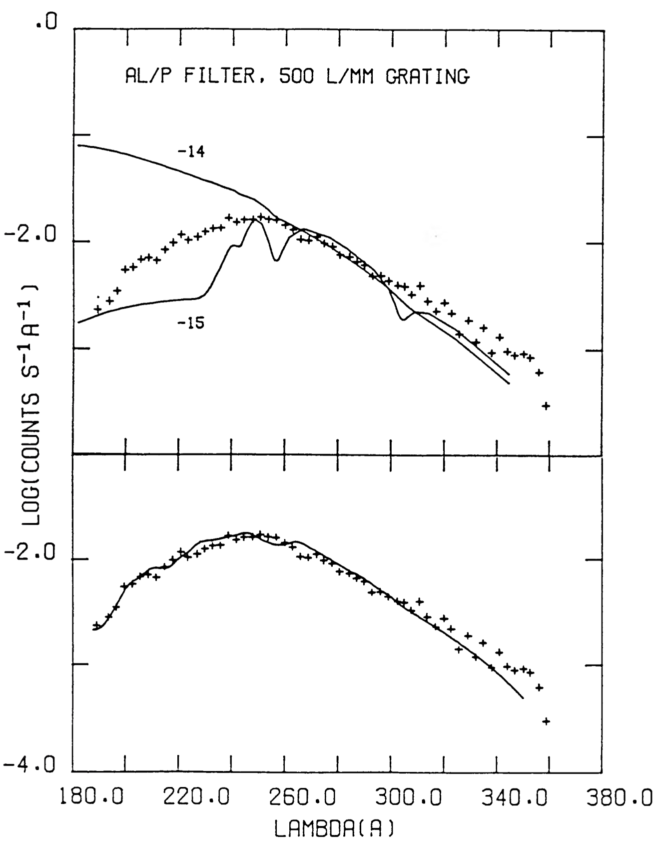

FIG. 1.—(*top*) Count rate spectrum of Feige 24, as observed with Transmission Grating Spectrometer and Al/P filter (*crosses*). Shown here as well are two stratified model atmospheres at $T_e = 50{,}000$ K, log $g = 8.0$, and fractional hydrogen layer masses of 10^{-14} (*upper curve*) and 10^{-15} (*lower curve*). Both models include an attenuation by an interstellar column density $n_{\mathrm{H}} = 3.5 \times 10^{18}$ cm^2, and are scaled to match the observed V magnitude ($V = 12.56$). (*bottom*) Same as top panel, but for a hydrogen-dominated, homogeneous model atmosphere at $T_e = 55{,}000$ K, log $g = 7.23$ with traces of numerous heavy elements.

III. A SECOND LOOK AT METALS IN THE ATMOSPHERE OF FEIGE 24

The rather surprising results presented in § II has prompted us to look for alternatives to the stratified atmosphere, and to consider, in particular, an alternate possibility which was alluded to in Vennes *et al.* (1988). It has been recognized at the outset in earlier investigations that the required soft X-ray/EUV opacity source needed to explain the observations of hot DA stars may not be totally provided by helium but also, in some part, by heavier elements. It was for reasons of simplicity that helium became the favorite absorber. In the the case of Feige 24, the known presence of C, N, and Si has remained suggestive, even though Paerels *et al.* (1986) concluded that models with traces of these elements could not account for the EUV spectrum. This is because the *IUE* window can only reveal a relatively small number of metallic resonance lines, and the detection of C, N, and Si only in the *IUE* spectrum of Feige 24 in no way implies a lack of other elements in the atmosphere. Quite the contrary, if small abundances of C, N, and Si are supported by radiative levitation, we expect that a host of other elements can be supported as well. Thus, we envision a situation in which many different metals *with low abundances* are present in the atmosphere of Feige 24. These metals would lead to a large number of *small* absorption edges which are smoothed over because of the finite resolution of *EXOSAT* ($\sim$6 Å), and whose cumulative effect is to quench the short-wavelength flux.

As an illustrative example, we have computed the synthetic EUV spectrum of a model of Feige 24 with log $g = 7.23$ and $T_e = 55{,}000$ K. The model is hydrogen-rich with small uniform traces of 10 elements: He, C, N, O, Ne, Na, Si, S, Ar, and Ca. These particular elements were chosen for the presence of photoionization edges in the 190–350 Å *EXOSAT* range and for the *absence* of resonance lines (except for C, N, and Si) in the 1200–3000 Å *IUE* range at the effective temperature of interest. It is important to note that the individual abundances chosen for this illustration are (save for Ar and Ca) at or below solar, and are consistent with those predicted from radiative support theory. Indeed, equilibrium abundance profiles are

TABLE 1

ELEMENT ABUNDANCES IN ILLUSTRATIVE MODEL

Element	Z/H
He	1.0×10^{-5}
C	7.0×10^{-6}
N	7.0×10^{-6}
O	5.0×10^{-6}
Ne	1.0×10^{-6}
Na	1.0×10^{-7}
Si	1.0×10^{-7}
S	2.0×10^{-5}
Ar	3.0×10^{-5}
Ca	2.5×10^{-4}

NOTE.—All abundances are number ratios.

already available in Chayer, Wesemael, and Fontaine (1988) for C, N, O, and Si. Profiles for several additional elements between C and Fe were computed as well within the cruder formalism of Michaud *et al.* (1976) for the calculation of the radiative acceleration. While current evidence suggests that weak winds may have a role to play in determining the atmospheric abundance of specific elements (Chayer *et al.* 1987; Chayer, Fontaine, and Wesemael 1988), it seems clear that these equilibrium abundances provide a realistic estimate of abundances that *could* be supported in the atmosphere of Feige 24. The individual abundances adopted are given in Table 1; slight adjustments with respect to the predictions of radiative support theory have been made for some elements.

Figure 1*b* shows the count rate spectrum predicted from such model atmosphere calculations together with the Feige 24 data. The agreement is gratifying. Of course, we cannot pretend that there exists a unique fit; our choice of absorbers is somewhat arbitrary and other possibilities exist. We have left out a potentially great number of absorbers, and a detailed comparison at the level of small residual features in the theoretical curve cannot realistically be made. In fact, the prospect for such a comparison remains unlikely until we understand in detail what governs the relative and absolute abundances of trace species in the atmospheres of hot white dwarfs. We know that the predictions of simple radiative support theory—which assumes a perfect equilibrium between gravitational settling and radiative levitation—are not entirely consistent with the observations. It is thought that weak winds may play havoc with the abundances of some metals supported by radiation in hot white dwarfs (Chayer *et al.* 1987; Chayer, Fontaine, and Wesemael 1988). Until a decent theory of these phenomena becomes available, we must remain satisfied with the qualitative picture described here. We strongly believe, however, that the basic idea is correct: *the EUV spectrum of Feige 24 can simply be explained by the cumulative effects of a host of trace absorbers in a hydrogen atmosphere.*

IV. CONCLUDING REMARKS

If the picture presented in § III is indeed correct, it raises a number of interesting questions concerning the interpretation of EUV/soft X-ray data in terms of layered atmospheres. In particular, is Feige 24 an exception or a typical DA white dwarf? A qualitative comparison between the DA stars observed in the EUV range as discussed by Vennes *et al.* (1988) and the sample of DA objects observed at high resolution with the *IUE* by Bruhweiler and Kondo (Bruhweiler 1985) is of interest here. We find, from the limited information available, that seven objects out of seven which require an EUV opacity source *also* show some metallic features in their *IUE* spectra. Are these all similar to Feige 24 in the sense that their EUV fluxes are regulated by a cumulative metallic opacity? In that case, there would be no need to invoke thin hydrogen layers for those stars. We find this possibility rather suggestive, but we cannot be certain because, except for Feige 24, we do not know the abundances of the elements detected with the *IUE*, and the photospheric nature of the features may be difficult to ascertain. And, indeed, we also find three objects in the EUV sample which do *not* require an EUV opacity source (i.e., they emit like pure hydrogen models) and, yet, also show metallic features in their *IUE* spectra. At the very least, this suggests that the abundances of the metals detected must be very small in order not to quench significantly the EUV flux. Thus, the presence of metals in the *IUE* spectrum of a DA star does not necessarily eliminate the need for a layered atmosphere. Nevertheless, our suggested model for the EUV spectrum of Feige 24 further muddles an already complicated story.

In that context, it should be remembered that the case for layered atmospheres is very strong for the DAO stars which are hot progenitors of ordinary DA stars. Vennes *et al.* (1988) find that this model is the only viable one for that type of objects. As evolution proceeds, DAO stars cool to become ordinary DA stars and, therefore, must retain their layered configurations. The observations of the DAO object PG 1210+533 by Holberg *et al.* (1988) reinforce strongly the conclusion of Vennes *et al.* (1988). Thus, it may very well be the case that the effects of *both* H/He stratification and metallic absorption regulate the EUV flux of hot DA white dwarfs. The opacity could be dominated in some stars (such as Feige 24) by metallic absorption, in other stars by H/He stratification (in cases where a wind has expelled the heavy elements from the star, for example), and in other cases by both mechanisms. Before the question is definitely settled, we will have to await the results of future experiments, such as EUVE and ROSAT, which should provide a definitive test. The available *Einstein* and *EXOSAT* photometric observations can currently be understood either within the framework of H/He layered atmospheres or within the framework of metallic absorbers. The answer lies with EUV *spectroscopy*, since uniform models, stratified models, and models with metals have quite different spectral signatures.

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