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He I λ4471 PROFILES IN B STARS: CALCULATIONS WITH AN IMPROVED LINE-BROADENING THEORY

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ABSTRACT

Theoretical profiles for the He I λ4471 line in B-star spectra have been computed using an improved broadening theory of Barnard, Cooper, and Smith, together with level populations determined by a self-consistent solution by Auer and Mihalas of the coupled transfer and statistical-equilibrium equations. The broadening theory has been constructed to provide a more accurate description of the intensity and width of the forbidden ($2p\ ^3P^o$–$4f\ ^3F^o$) transition as measured in laboratory experiments. The results presented in this paper show that this revision of the broadening theory leads to computed stellar profiles which are in much better agreement with observed profiles than any previously obtained.

Subject headings: early-type stars — line profiles

I. INTRODUCTION

The helium spectrum in B stars has attracted the attention of astrophysicists ever since the pioneering work of Struve (1928, 1931, 1935). Analysis of the helium spectrum offers opportunities both to infer the helium/hydrogen ratio, and to perform diagnostics of the prevailing physical conditions in stellar atmospheres. Two substantial obstacles which have repeatedly thwarted attempts to capitalize upon these opportunities are: (*a*) the need for accurate Stark profiles of the relevant lines as a function of temperature and perturber density, and (*b*) the necessity of determining the occupation numbers of the appropriate atomic levels in a manner self-consistent with the radiation field in the atmosphere. Considerable progress has been made toward removal of these obstacles in recent years. Detailed calculations of helium-line Stark profiles have been published by Griem *et al.* (1962, hereinafter referred to as GBKO), Griem (1968), Barnard, Cooper, and Shamey (1969), and Gieske and Griem (1969). These have been used by several authors to interpret stellar profiles (see, e.g., Leckrone 1971). The problem of obtaining self-consistent solutions of the coupled transfer and statistical equilibrium equations has been addressed by Auer and Mihalas (1973, hereinafter referred to as AM), who showed that allowance for departures from LTE in the analysis of the helium spectrum significantly improved the agreement between theory and observation.

Despite these advances, there has remained a serious discrepancy between the observed and computed profiles for the important diffuse-series lines, the higher members of which show marked asymmetries and the presence of strong "forbidden" components. Among these lines the λ4471 line ($2p\ ^3P^o$–$4d\ ^3D$) is perhaps the most important, for it is a strong line, easily observable at even low dispersion, in the accessible photographic region of the spectrum. Careful comparison of accurately observed profiles with those computed on the basis of the work cited above shows that the computed forbidden component is too narrow and too deep, and that the line-opacity in the wavelength region between the forbidden and permitted components is too low (see, e.g., AM; Leckrone 1971; Norris 1970, 1971; and Snijders and Underhill 1971). A similar discrepancy has been found in comparing the theoretical profiles with laboratory experiments (e.g., Burgess 1970; Burgess and Cairns 1970).

To resolve these difficulties, a new quantum-mechanical calculation of the λ4471 Stark profiles has been carried out by Barnard, Cooper, and Smith (1974); these results are now in good (~10%) agreement with the experimental data. The salient features of this work are outlined in the next section. Stellar profiles are presented and compared with observation in § III, and our principal conclusions are stated in § IV.

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II. OUTLINE OF THE PHYSICS OF THE LINE-BROADENING THEORY

The original calculations of Griem (1968) and Barnard *et al.* (1969) computed the broadening of λ4471 using the impact approximation for the electrons (following GBKO 1962) and the quasi-static approximation for ions. However, as pointed out by Burgess (1970), the ions cannot be considered as static for determining the profile in the region of the forbidden component, and so-called "ion dynamic" effects have to be taken into account.

To take ion dynamics into account Barnard *et al.* (1973) have extended the "adiabatic" treatment of GBKO (1962) (which treats the interaction with the ions in terms of a scalar phase-shift by averaging over *m*-states) to include the forbidden line as well as the allowed line (see Cooper, Smith, and Chappell 1971 for a preliminary description of this technique). The treatment also includes, for the forbidden line, terms referred to by Burgess (1970) as "non-adiabatic." This theory should be especially valid at low electron densities (of astrophysical interest) when the forbidden and allowed components are fairly well separated. In addition, the profiles obtained are found to approach closely the previous static-ion calculations for densities greater than $\sim 5 \times 10^{15}\ \mathrm{cm}^{-3}$. Barnard *et al.* (1973) also find good agreement with the calculations of Lee (1973) in spite of the fact that Lee's theory is quite dissimilar to the adiabatic treatment of ion dynamics.

III. COMPUTED PROFILES AND COMPARISON WITH OBSERVATION

The computational procedure is identical to that described by AM and will not be discussed again here. The model atmospheres are those of Mihalas (1972) and the helium level-populations are those of AM. In all cases the assumed helium to hydrogen ratio is $N(\mathrm{He})/N(\mathrm{H}) = 0.10$. The resulting equivalent widths are presented in table 1, and line profiles at selected wavelengths are listed in table 2. The relationships between the LTE and non-LTE profiles are essentially the same as those found by AM. The equivalent widths are slightly (up to 5%) larger than those found earlier. This results from the greater breadth of the

TABLE 1

He I λ4471 EQUIVALENT WIDTHS*

T_{eff} (° K)	log *g* 4.0 LTE	4.0 NLTE	3.0 LTE	3.0 NLTE	2.5 LTE	2.5 NLTE
15,000......	0.662	0.695	0.641	0.660	0.569	0.573
17,500......	1.104	1.119	0.879	0.853	0.648	0.600
20,000......	1.423	1.389	0.908	0.837	0.542	0.479
22,500......	1.474	1.398	0.788	0.717	...	...
25,000......	1.349	1.258	0.635	0.610	...	...
27,500......	1.187	1.125	0.321	0.539	...	...

* $N(\mathrm{He})/N(\mathrm{H}) = 0.10$.

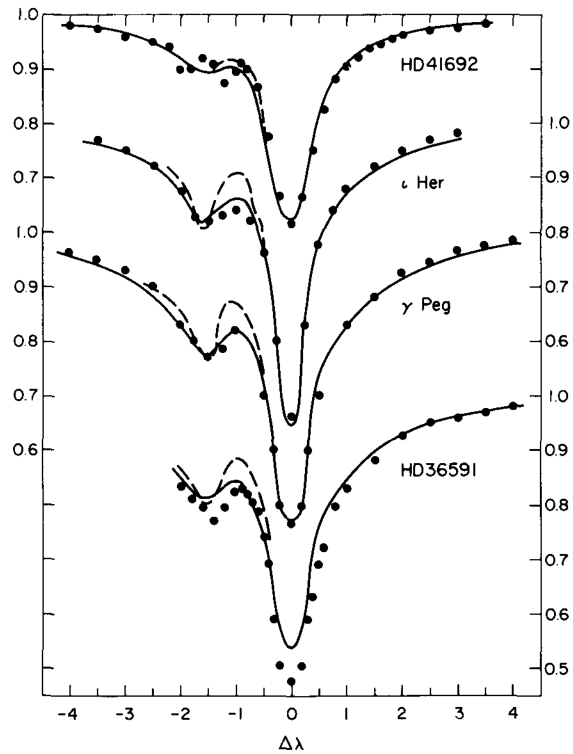

FIG. 1.—Comparison of observed and computed He I λ4471 line profiles. *Filled circles*, observed data. *Solid curves*, calculated non-LTE profiles using improved broadening theory. *Dashed curve*, calculated non-LTE profiles using Barnard *et al.* (1969) broadening theory. *Ordinate*, residual flux in units of the continuum. *Abscissa*, Δλ in Å.

forbidden component, and from a higher opacity between the permitted and forbidden components, which substantially reduces the emitted flux on the range $-1.25\ \mathrm{Å} \leq \Delta\lambda \leq -0.5\ \mathrm{Å}$. The contrast (i.e., residual-flux difference) between the intercomponent flux maximum (near $\Delta\lambda = -1.0$ Å) and the minimum at the center of the forbidden component (near $\Delta\lambda = -1.5$ Å) is reduced from a maximum of 15 percent to only 7 percent, which is a very substantial change. Both the central depth of the line, and the shapes of the entire red wing and of the far-blue wing, are essentially unaltered by the present results. Thus earlier spectral diagnostics based upon these properties of the line profile should be unaffected.

A comparison with selected observed profiles is shown in figure 1. The sources of the data are given in AM. As was done in the earlier comparison, we have interpolated linearly in T_{eff} and log *g*, and have chosen those parameters which best match the observed line profile. The final choices of (T_{eff}, log *g*, and *v* sin *i*) are: (16,000, 3.2, 30) for HD 41692; (18,500, 3.8, 5) for ι Her; (22,500, 4.0, 10) for γ Peg; (26,500, 4.0, 15) for HD 36591. These values differ from those adopted by AM by no more than 500° K and 0.2 in T_{eff} and log *g*, respectively; the values of *v* sin *i* are the same as those used by AM. Given the coarseness of the model grid and the simple interpolation pro-

Table 2

Profiles of He I λ4471

Model			Δλ																
T_{eff}	log g	Theory	-6.00	-4.00	-3.00	-2.00	-1.75	-1.50	-1.25	-1.00	-.40	0.00	.40	1.00	1.50	2.00	3.00	4.00	6.00
15000	4.0	NLTE	.992	.982	.967	.932	.914	.894	.913	.928	.872	.537	.803	.912	.945	.962	.979	.988	.995
15000	4.0	LTE	.993	.982	.967	.933	.915	.895	.914	.929	.874	.623	.811	.912	.946	.962	.979	.988	.995
15000	3.0	NLTE	.996	.989	.977	.941	.923	.890	.910	.928	.868	.433	.803	.927	.956	.971	.986	.992	.997
15000	3.0	LTE	.996	.988	.977	.939	.919	.886	.907	.926	.863	.547	.799	.924	.955	.970	.986	.992	.997
15000	2.5	NLTE	.998	.994	.987	.959	.943	.901	.926	.944	.881	.411	.801	.945	.970	.982	.992	.996	.998
15000	2.5	LTE	.997	.993	.986	.956	.938	.892	.920	.940	.870	.526	.786	.941	.968	.980	.991	.995	.998
17500	4.0	NLTE	.985	.965	.939	.883	.855	.825	.850	.873	.797	.419	.723	.855	.904	.931	.959	.977	.990
17500	4.0	LTE	.985	.964	.937	.880	.852	.822	.847	.870	.793	.526	.723	.852	.901	.929	.958	.977	.990
17500	3.0	NLTE	.994	.985	.970	.919	.893	.845	.874	.898	.817	.389	.735	.899	.939	.960	.982	.990	.996
17500	3.0	LTE	.994	.984	.968	.912	.884	.830	.862	.889	.798	.501	.709	.890	.934	.957	.980	.989	.996
17500	2.5	NLTE	.998	.995	.989	.964	.948	.880	.927	.944	.862	.406	.756	.945	.972	.983	.993	.996	.998
17500	2.5	LTE	.998	.994	.987	.960	.942	.855	.915	.935	.834	.505	.702	.936	.967	.980	.992	.995	.998
20000	4.0	NLTE	.981	.954	.919	.846	.813	.776	.803	.830	.745	.407	.676	.814	.873	.908	.947	.970	.987
20000	4.0	LTE	.981	.952	.916	.837	.802	.762	.791	.820	.728	.503	.657	.804	.867	.904	.944	.969	.987
20000	3.0	NLTE	.995	.987	.973	.922	.895	.841	.873	.899	.809	.416	.715	.900	.943	.964	.983	.991	.997
20000	3.0	LTE	.995	.985	.970	.913	.882	.814	.855	.885	.777	.492	.662	.887	.936	.959	.982	.990	.996
20000	2.5	NLTE	.999	.997	.994	.980	.970	.910	.953	.965	.893	.449	.774	.966	.983	.990	.996	.998	.999
20000	2.5	LTE	.999	.997	.993	.978	.966	.883	.944	.958	.863	.504	.698	.959	.980	.988	.995	.997	.999
22500	4.0	NLTE	.982	.955	.919	.840	.806	.768	.794	.822	.736	.428	.671	.809	.870	.908	.947	.971	.988
22500	4.0	LTE	.981	.952	.914	.828	.790	.745	.775	.806	.709	.489	.639	.793	.860	.901	.944	.969	.987
22500	3.0	NLTE	.997	.991	.980	.939	.915	.866	.895	.917	.831	.453	.732	.920	.956	.973	.988	.994	.998
22500	3.0	LTE	.996	.990	.978	.932	.905	.842	.880	.907	.801	.494	.675	.910	.951	.970	.987	.993	.997
25000	4.0	NLTE	.985	.962	.929	.856	.824	.788	.812	.837	.755	.467	.693	.825	.884	.919	.955	.976	.990
25000	4.0	LTE	.984	.960	.925	.844	.807	.765	.793	.822	.725	.495	.651	.810	.875	.914	.953	.974	.989
25000	3.0	NLTE	.998	.994	.987	.956	.936	.894	.918	.937	.852	.476	.744	.940	.969	.981	.992	.996	.998
25000	3.0	LTE	.998	.994	.987	.954	.933	.886	.913	.934	.837	.515	.703	.938	.968	.981	.992	.996	.998
27500	4.0	NLTE	.988	.968	.940	.873	.842	.810	.831	.855	.773	.490	.708	.843	.899	.932	.963	.980	.992
27500	4.0	LTE	.988	.968	.938	.866	.831	.793	.818	.845	.748	.515	.668	.833	.895	.929	.962	.980	.992
27500	3.0	NLTE	.999	.997	.992	.971	.956	.919	.940	.955	.862	.470	.731	.959	.980	.989	.995	.998	.999
27500	3.0	LTE	1.000	.999	.997	.988	.980	.961	.972	.980	.917	.663	.812	.982	.992	.996	.998	.999	1.000

cedure, the differences are probably not significant. We stress that these parameters are based upon a fit to one line only, and are not necessarily unique nor optimum choices; higher precision in determining these quantities can be obtained only by an analysis of several lines, with models constructed at, or very near to, the final choices of T_{eff} and log *g*. Even in the face of these caveats it is obvious from inspection of the figure that an excellent fit (within observational error) to the observations is now obtained. The worst discrepancies occur for HD 36591 where both the permitted and forbidden component cores are computed too shallow. Possible physical reasons for these discrepancies have been discussed by AM; almost certainly they reflect errors in the statistical equilibrium solution and not the Stark profiles themselves.

IV. CONCLUSIONS

The main result of this paper is that we have shown that the improved He I λ4471 line-broadening theory of Barnard *et al.* (1973) yields theoretical stellar profiles which, for the first time, are in excellent agreement with observation. We thus obtain an important independent check upon the line-shape calculations in temperature-density regimes that are quite difficult to produce in the laboratory. Further, we have shown that a sufficiently good match can be obtained to observed λ4471 profiles to allow them now to be analyzed with confidence and precision. Moreover, the results of AM indicate that for B stars (but *not* O stars) the λ4471 line profile is affected by departures from LTE only at line center ($|\Delta\lambda| < 0.5$ Å), so that ordinary LTE calculations may be used with confidence to generate wing profiles at arbitrary values of T_{eff}, log *g*, and *N*(He)/*N*(H). For the O stars ($T_{eff} >$ 30,000° K), a full non-LTE analysis is necessary. It is perhaps not an overstatement to remark that only now, a full 40 years after Struve's first attempts, we finally have what appears to be a satisfactory theoretical basis for the interpretation of He I λ4471 line profiles. It will be of interest to extend the improvements in the line-broadening theory to other lines of astrophysical interest for which discrepancies with the observations still exist (e.g., He I λ4921). We hope to carry out this work in the near future, and will report results as they become available.

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