SPECTRA OF WHITE-DWARF STARS AT WAVELENGTHS < 3000 A: A THEORETICAL PERSPECTIVE

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I. INTRODUCTION

Astronomers studying objects outside the solar system first used the ultraviolet, extreme ultraviolet, and x-ray regions of the electromagnetic spectrum in the 1970s. The exploration of these wavelength regions has produced considerable improvements in our understanding of these objects. The achievements of x-ray astronomy are perhaps the best known. With the advance of satellite technology, other wavelength regions begin to play a role, and x-ray astronomy moves into the luminosity domain where quiescent as well as violent astrophysical processes can produce detectable amounts of radiation. This paper reviews the current state of our interpretation of white-dwarf stars at wavelengths less than 3000 A.

Have the satellite observations of white-dwarf stars provided insight as well as data? There is no question that they have. To start with the prosaic, ultraviolet and extreme-ultraviolet (EUV) observations have confirmed the values of T(eff) determined from optical data, thereby placing recent determinations of white-dwarf radii on a firmer footing. These spectral regions have already provided new and more sensitive ways of probing the helium content of hot white-dwarf atmospheres. Many chemical species have absorption features, lines or edges, in the short-wavelength regions under discussion, and analysis of the newly available data should allow for considerable improvements in our understanding of the chemical composition of white-dwarf atmospheres,since these atoms (for example C,N, and O) have no prominent spectral features in the visible. White dwarf stars have a more varied composition than main-sequence stars do, and understanding why there are some H-rich and some He-rich white dwarfs is an important frontier of current research. The EUV has provided new and surprising information on the interstellar medium: in some directions there is very, very little neutral hydrogen. In some objects, high-energy emission is produced by accretion processes.

Section II of this review discusses the various mechanisms that produce radiation at wavelengths less than 3000 A. Thermal (but not black body) radiation from stellar photospheres is reviewed most extensively. Section III discusses the analysis of existing data on most objects; the enigma of Sirius B is reserved for section IV.

II. EMISSION MECHANISMS

How do astronomical objects raddiate at wavelengths less than 3000 A? Before you can learn anything about the nature of an object producing radiation, you first need to learn what is producing the radiation so that you can construct an adequate model. Consider several possible emission processes.

Optically Thick Plasmas (Stellar Photospheres)

This form of radiation is one of the most thoroughly observed and modelled in astrophysics. One of the stellar atmosphere textbooks can provide a complete discussion of the relevant processes (Gray 1976, Mihalas 1970, for example). However there are some aspects of the problem which are important in the interpretation of ultraviolet, EUV, and x-ray data which are worth emphasizing here.

The emergent flux from a stellar atmosphere can be written as

$$H_{\nu}(\tau=0)=\int_{0}^{\infty}E_{2}(dt)\;S_{\nu}(t)\;d\tau \qquad (1)$$

where S is the source function, E_2 the second exponential integral, and τ the optical depth at a particular frequency. H_ν is the emergent Eddington flux in ergs/cm^2/sec/steradian/Hz. The source function is determined by solving the transfer equation

$$\mu\, dI/d\tau = I - S \qquad (2)$$

where S is defined as

$$S_{\nu}=(\kappa_{\nu}/[\kappa_{\nu}+\sigma_{\nu}])\,B_{\nu}+(\sigma_{\nu}/[\kappa_{\nu}+\sigma_{\nu}])\,J_{\nu} \qquad (3)$$

at each frequency. In this notation the Planck function is $B_\nu = 2h\nu^3/c^2(\exp(h\nu/kT-1)$. The solutions to equations 1 through 3 are subject to the constraint of energy balance

$$\text{H(radiative)} + \text{H(convective)} + \text{H(conductive)} = \sigma T^{4}/4\pi \qquad (4)$$

which must be valid at all depths. So far, the conductive term has not been considered to be important.

Do you need to use model atmospheres? The solution of equations (1) through (4) requires complex computer programs; it would seem easier to write

$$H_{\nu}= B_{\nu}(T(\text{eff}))/4 \qquad (5)$$

assuming that the object radiates like a black body. (The factor of 4 in eq. (5) comes from the normalization of the Eddington flux, eq.4.) This approach has been adopted in some analyses (Margon et al. 1976b, Koppen and Tarafdar 1978). Because this approach fails in even a preliminary analysis of data in the EUV, some discussion of why it doesn't work and where it might work is in order.

You can understand what goes on by approximating the exponential function E (x) by a delta function, say δ (x-1). Further assume that scattering is unimportant so that S = B. This way, equation 2 and equation 4, the source of all the complexities of model-atmosphere calculations, become unnecessary, and equations 1 and 3 collapse to the simple form

$$H_\nu = B_\nu(\tau_\nu=1)/4 \qquad (6).$$

Numerical calculations verify that equation 6 is not a bad approximation in the absence of scattering.

Equation 6 is not the same as the black-body approach of equation 4. The temperature at monochromatic optical depth unity can vary quite dramatically with wavelength where the opacity changes with wavelength. In transparent spectral regions like the EUV and X-ray regions (for He- and metal-poor atmospheres), you can see very deep into the atmosphere, observing a high-temperature layer (Figure 1). Optical spectroscopy has shown that many white-dwarf stars do indeed have low He and metal abundances (see, for instance, Liebert 1977, Shipman 1972,1977a; Strittmatter and Wickramasinghe 1971; Wegner 1972). Therefore, departures from from a black body spectrum can be expected in white dwarf atmospheres (see Figure 2).

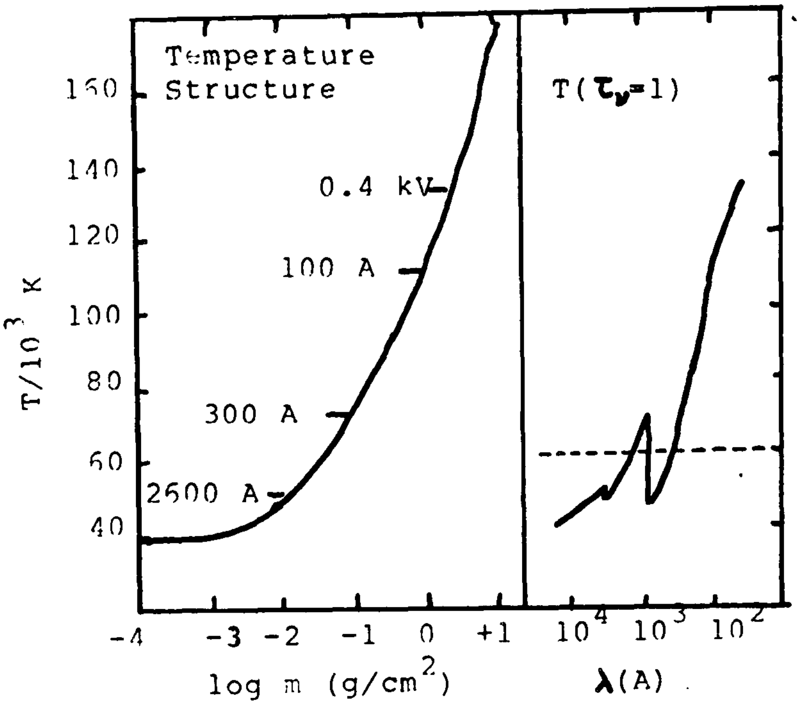

Figure 1. Left: The temperature distribution in a T(eff)=60,000 K, log g = 8 pure hydrogen model atmosphere. The layers where monochromatic optical depth equals unity in various spectral ranges are indicated. Right: The temperature at monochromatic optical depth unity as a function of wavelength. This temperature is approximately the equivalent temperature that the star radiates at in those wavelengths.

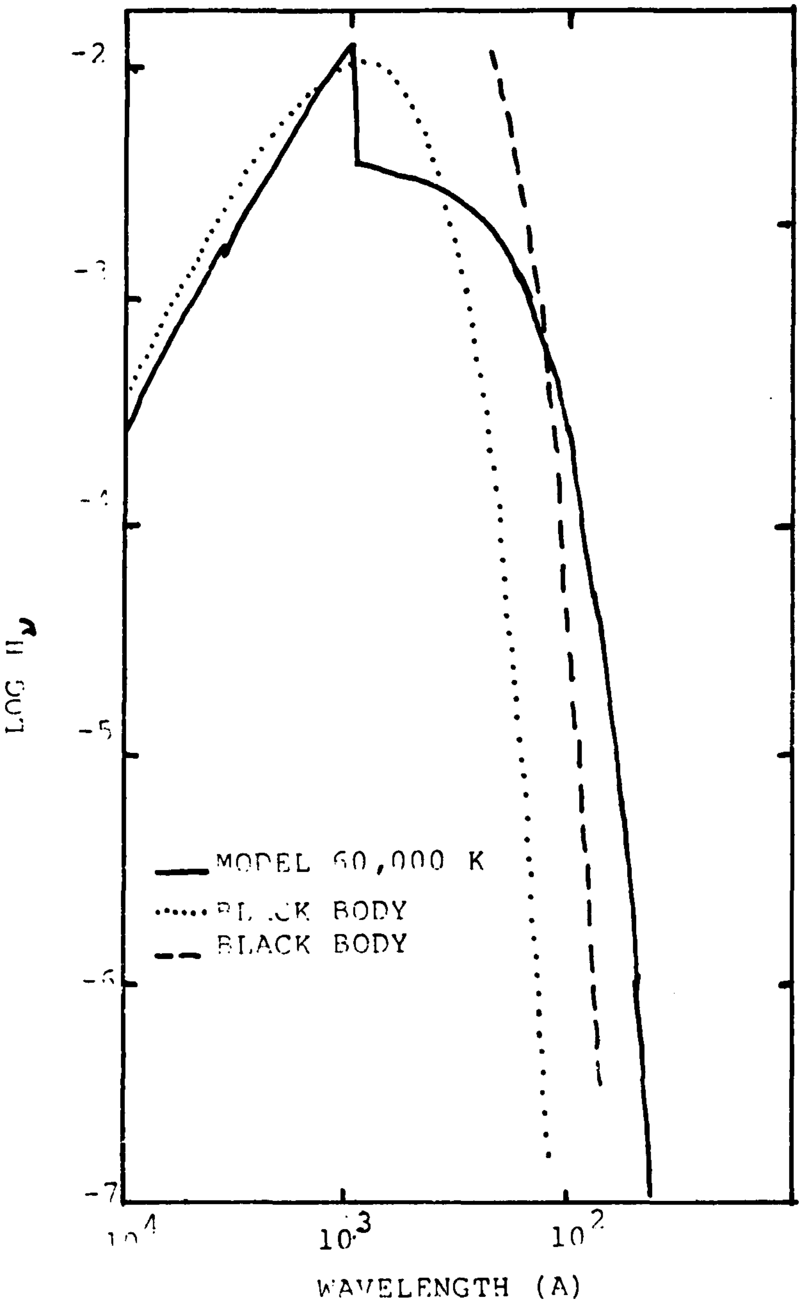

Figure 2. The emergent flux distribution from a T(eff)=50,000 K, log g = 8 pure hydrogen model atmosphere. Non-LTE effects are included. The dotted line shows a black body with T = T(eff) = 50,000 K, and the dashed line shows a black body with T = 100,000 K.

Based on the preceding discussion, a black-body analysis of a stellar atmosphere can work in an approximate way if several conditions apply. Absorption must dominate over scattering. If the spectral range of interest is at wavelengths short of the peak of the Planck distribution, the Planck function and hence the source function will be less depth dependent. If the opacity does not vary too much with wavelength, you will be looking at the same layer of the atmosphere in various spectral ranges and a black body fit to the spectrum will not be outrageously bad. In the visible and ultraviolet spectral regions, these conditions hold in an approximate way for hot stars, and so temperatures from black body analyses should not be too bad. However, in metal-poor stars, the last two conditions do not hold in the EUV and none holds in the x-ray range, and so black body temperatures can be quite misleading. This phenomenon was first applied to the case of Sirius B by Shipman (1976). While that particular analysis may be flawed (see below), these types of models do fit hot white dwarfs like HZ 43.

With the complexity of model atmosphere calculations, one of the questions that always comes up is the accuracy of those calculations. Cross-checks between different computer programs are always useful in approaching this question. Auer and Shipman (1977) mentioned the results of one such comparison, and I referred to another in Shipman (1979). On the basis of these checks, it is evident that the uncertainties that are attributable to numerical errors are quite small (on the order of a percent).

A potentially more serious problem is the degree of confidence one has in the physics used in the model. I briefly summarize the problems here. At very low temperatures and high densities, the ideal gas equation of state may not be accurate enough. In an important paper,Böhm et al. (1977) showed that a T(eff) = 4,000 K, pure He model star would be degenerate at the surface. Checking my own models shows that for T(eff) = 6,000 K in the hydrogen models and for T(eff) = 10,000 K in the helium models, the ideal gas equation of state differs from that of Fontaine et al. (1977) by 20 %, and the ideal gas equation becomes a worse approximation at lower T(eff). Convective energy transport carries a significant amount of flux for T(eff) < 12,000 K (hydrogen-rich models; Shipman 1972, 1977a) and T(eff)<50,000 K (helium-rich models; Fontaine and Van Horn 1976). I(Shipman 1977a,1979) have explored the effects of changing the convective effeciency parameter 1/H from 1 to 3 and from 1 to 0.3, showing that the continuum fluxes are changed by the order of 5 to 10 %. So far, the structure of white-dwarf atmospheres has been calculated using LTE as an approximation to determining the populations of atomic states (and thus the opacities that enter equation 3). Greenstein and Peterson (1973) and Kudritzki (1976;see also Wesselius and Koester 1978) showed that at log g = 8 the LTE approximation is safe to T(eff) = 100,000 K., though details have only been published to T(eff) = 50,000 K. In He-rich models, the absorption coeffecient of the negative helium ion dominates, and its value is poorly known. As far as I know no one has explored the possible effects of this uncertainty. At lower gravities, too, the plane-parallel approximation is not valid (Kunacz et al. 1975),though at log g = 8 this approximation seems all right for all temperatures considered so far. This problem was first pointed out in connection with white dwarfs by Böhm and Cassinelli (1969). Calculation of line profiles is a little more uncertain than calculation of continuum fluxes, since the temperature distribution at shallow optical depths is relatively more affected by some of the problems mentioned in this paragraph. Preliminary comparisons of results obtained to date indicate that the uncertainties are probably less than 15 %.

To review: There are various potential problems. However, in the white-dwarf range of T(eff) and log g, most of these problems show up at the cool temperatures, particularly for the hydrogen-rich models. There is no known problem with the physics of high-temperature (T(eff)>12,000 K), log g = 8 hydrogen-rich models, as far as the calculation of continuum flux is concerned.

A number of grids of model atmospheres have been published. Table 1 summarizes the grids which have been published or are in press at this time, to my knowledge;Ihave not included those studies where a few models were calculated for studies of specific stars (e.g., the models done for van Maanen 2 by Grenfell, Hammond, and Wegner in the early 1970s, and the models for the λ4670 stars).

Table 1
Published Grids of Model Atmospheres

T(eff) Range	log g	Reference	Remarks
Hydrogen-Rich Models			
5,000-50,000	7,8	Shipman(1971, 1972)	Fluxes only were published
10,000-25,000	6,7,8,9	Wickramasinghe (1972)	No convection He/H=0.144
7,000-12,000	7,8,8.5	Wehrse(1975,1976)	No Lyman line blanketing No convection
40,000-50,000	4-8	Kudritzki(1976)	Investigation of non-LTE effects
7,000-100,000	7,8,9	Kiel group	See Koester et al. 1979b
8,000-120,000	7,7.5,8,8.5	Shipman	To be published
20,000 and up	4 - 9	Rochester group	To be published (see Wesemael et al. 1979)
He-Rich Models			
10,000-25,000	7,8	Shipman (1972)	Fluxes only were published
15,000-25,000	7,8,9	Wickramasinghe (1972)	He/H=10,000
12,000-30,000	7,7.5,8	Koester(1980)	He/H=100,000 Line blanketing in

Optically Thin Plasmas (Coronas)

Emission in the ultraviolet, EUV, and x-ray parts of the electromagnetic spectrum can also be produced by coronas. Observations of the sun in these spectral ranges have been made routinely for at least 20 years. Our knowledge of the complexities of the chromosphere, transition region, and corona of the sun has increased substantially.

Copernicus and IUE satellite observations of stellar coronas have brought about the exciting arena of applying solar physics to understand stellar physics (see, for instance, Linsky et al. 1978). If white-dwarf stars have coronas, they will emit in the spectral range under consideration in this review.

There has, so far, been no unambiguous detection of coronas around single white-dwarf stars. Several stars show emission cores in hydrogen lines, and these objects might be good targets for x-ray missions. If there are coronas around them, and if(by analogy with the sun) the coronas contain high-temperature gas, they should be reasonably strong x-ray sources. Single white dwarfs currently classified as showing emission lines are WD0135-05 (=EG 11, L 870-2; Greenstein et al. 1977); WD 0518+33 (=EG 43); WD 0732-42 (=Wegner 9), WD 0855+60B(=EG 172), and BPM 18764 (Wegner 1979b). The WD numbers are from the catalog of McCook and Sion (1977) which refers to the discovery papers. Other interesting emission-line objects include GD 552, a white-dwarf star which is apparently losing mass (Giclas and Greenstein 1979) and WD 1303+18 (G 61-29), an object which shows helium emission lines (Burbidge and Strittmatter 1970). The possibility of these stars having coronas has not so far been investigated beyond their classification as emission-line white dwarfs. This list excludes novae and white dwarfs with composite spectra.

The first suggestion that white-dwarf stars might have coronas was made by Böhm and Cassinelli (1971). They showed that the outer convection zones of He-rich white-dwarf stars could produce fairly large acoustic fluxes, leading to coronal luminosities that could reach $\sim 10^{30}$ erg/sec. This field remained relatively dormant until the discovery of x-rays from Sirius. Since then, interest in white-dwarf coronas has revived.

There are two approaches that have been used so far in determining what coronas around white-dwarf stars will look like. The first, adopted by Böhm and Cassinelli (1971) and Fontaine (1977), examines the properties of convection zones and predicts acoustic fluxes. Based on the sun as a model, the idea is that the acoustic waves heat the corona to a temperature of $\sim 10^6$ K. The coronal x-ray luminosity will then be some considerable fraction of the acoustic flux. The most popular recipe for calculating acoustic fluxes is that of Lighthill (1955) where the acoustic flux is approximately

$$F(\text{acoustic}) = 19\,\rho v^8/c^5 \quad \text{ergs/s} \qquad (7)$$

where v is the maximum convective velocity and c is the sound speed, all in cgs units. The convective velocity is quite uncertain, as Böhm and Cassinelli (and all subsequent authors) point out. When you raise an uncertain quantity to the eighth power, the result is even more uncertain.

Hearn (1975) approached the coronal problem from a different perspective. Instead of worrying about the energy source, he asked the following question: "Suppose that something is dumping energy into a corona. What will the corona look like?" The corona will lose energy by thermal conduction into the photosphere, by losing mass by a stellar wind, and by radiation. The hypothesis is that a corona with a given base pressure will relax to a state that minimizes the energy lost by the above mechanisms-- hence the name of minimum-flux corona . Thus there is a single-valued family of coronas characterized by base pressures and temperatures. You can take a given energy input (that comes from a prescription of the energy source) and find out what the base pressure and temperature of the corona are. Hearn and Mewe (1976), Muchmore and Bohm (1978), and Lampton and Mewe (1979) all give examples of such families.

The calculation of properties of minimum-flux coronae depends on an accurate knowledge of the energy loss rate. In the two calculations where independent results can be compared, some caution regarding details seems indicated. Muchmore and Bohm (1978) and Lampton and Mewe (1979) both calculated minimum-flux coronas of pure He composition, and their results can be compared. Muchmore and Bohm's Figure 2 gives the acoustic flux F as a function of T(stellar), and their figure 1 can then be used to determine base pressures P and coronal temperatures T(coronal). Lampton and Mewe's Figure 2 gives a direct relationship between stellar temperature and coronal temperature Here the ML2 calculations of Fontaine (1977), used by both workers, are used to parameterize the coronal flux as a function of effective temperature. A comparison of the two calculations is shown in Table 2.

Table 2
Minimum-Flux Coronas of Pure Helium

	Lampton and Mewe	Muchmore and Bohm		
log T(stellar)	log T(coronal)	log F	log P	log T(coronal)
4.3	6.32	10.0	3.78	6.09
4.4	6.70	11.21	4.70	6.5

Evidently, for a given flux (parameterized by the stellar temperature in the first column), Muchmore and Bohm obtain coronas which are nearly a factor of 2 cooler than Lampton and Mewe obtain, as a comparison of the second and fifth columns in Table 2 shows. Apparently the difference is caused by Lampton and Mewe's introduction of a trapping factor, a factor that allows for the fact that the lines in white-dwarf coronae will supposedly be optically thick and not radiate too effectively. However, Lampton and Mewe offer no detailed justification. Evidently , in interpreting observations of white dwarf coronas, one need not regard the relationship between coronal flux and coronal temperature as something that is well-determined in detail. However, in all cases, coronal temperatures exceeding 10^6K are obtained. The spectrum expected from such a corona is a thermal bremsstrahlung spectrum along with free-free emission in some cases. Muchmore and Bohm (see their Figure 3) and Cash et al. (1978) provide some illustrations.

It should be emphasized that not all white-dwarf stars are expected to have coronas. To sustain a corona, energy must be supplied to the circumstellar plasma in some form. The traditional view is that this energy is supplied by convectively-generated acoustic flux. If this view is correct (and it may not be), only stars with T(eff) < 12,000 K (hydrogen-rich atmospheres) and T(eff)<50,000 K (helium-rich atmospheres) should have coronas if the atmospheres are homogeneous. Hearn and Mewe (1976) have proposed a chemically layered atmosphere for Sirius B, where despite the high hydrogen content of the photosphere, a helium subphotosphere has a convection zone and acoustic waves propagate upward through the hydrogen photosphere, feeding energy to the corona.

The whole problem of white-dwarf coronas needs to viewed in the context of our understanding , such as it is, of the coronas of other stars. In a recent review, Vaiana and Rosner (1978) point out some difficulties. They point out that the solar corona is neither homogeneous nor static, as the minimum-flux model assumes. Is a white-dwarf corona characterized by the same type of magnetically shaped loop structures that characterize the solar corona? Will a white-dwarf corona have coronal holes, regions where the gas density is very low? Because of these uncertainties, it seems to me that it would be premature to abandon the minimum-flux theory despite Vaiana and Rosner's implication that it is elegant but irrelevant. It may be hard to relate to the solar case, because we know so much. However, it has been useful in our understanding of other stellar coronas. Mullan (1978) showed that a high-temperature corona might or might not exist depending on a star's location in the HR diagram. The supersonic transition locus in the diagram, dividing hot coronas from cool coronas and stars losing mass from stars not losing mass, has been shown to exist by the IUE coronal observations of Linsky and Haisch (1979). Thus the minimum-flux concept has proven to be useful, and is particularly useful for white-dwarf studies because it allows you to do some calculations.

Another set of problems is related to the question of the energy source. The discovery of x-ray emission from stars in diverse parts of the HR diagram, in particular from A-type stars where no convection zones are expected to exist (and therefore no one expects coronas and coronal x-ray emission) (Giacconi 1979) has shown that we have a lot to learn yet. Ingham et al.(1976;see Strittmatter et al. 1972) suggested other mechanisms for energizing a corona: pulsations, accretion, and Alfven waves generated by magnetic fields seem possibly relevant to the white-dwarf case. Given these uncertainties, I feel that one should not rely too much on the details of any particular coronal model in the interpretation of observations.

Emission from Accreting White Dwarfs

Kylafis et al. (1979) have reviewed the theoretical predictions of radiation from accreting white-dwarf stars. The section of these proceedings devoted to AM Her objects should provide additional information. Consequently I shall just summarize the relevant emission mechanisms and scenarios here.

Radiation from a rapidly accreting white-dwarf star (or other compact object) is expected to arise from three distinct regions (see Kylafis and Lamb 1979; Kylafis et al. 1979). Accreting matter falls towards the star, and at sufficiently high accretion rates a shock front develops. The hardest component of the x-ray emission comes from the shocked, accreting gas. At sufficiently high accretion rates, this emission can be degraded by Compton scattering in the region outside the shock front. A second, softer component of radiation should be produced by thermal emission from the stellar surface. A third component of the spectrum comes from Compton-scattered radiation from gas that has not yet passed the shock front; this component is only expected where accretion rates are very high.

So far, the thermal radiation from the stellar atmosphere has been generally characterized as thermal. A few workers (see, for example, Perrenod and Shields 1972 and Milgrom 1976) have considered the departures from a black-body spectrum that would be expected. As long as the bremsstrahlung radiation, responsible for the extra heat input to the stellar atmosphere, is absorbed deep beneath the surface, the energy balance and boundary conditions will resemble those of a considerably hotter stellar atmosphere and the departures from black-body spectra considered above will still exist. Further analysis along these lines would be interesting.

The principal difference between spectra of accreting objects and the spectra of photospheres and coronas is that the accretion spectra, in the accretion ranges considered so far, are both harder and more luminous. Photospheres and coronas will not emit in the keV range; rapidly accreting objects like AM Her will. Thus confusion between a rapidly accreting source and a photosphere or chromosphere would seem unlikely. At lower accretion rates, current theory indicates that novalike phenomena would probably occur.

High-Energy Processes

A complete catalog of mechanisms that can produce high-energy radiation should include the synchrotron/inverse Compton processes that probably produce the x-rays that are seen in active galaxies and quasars. Here, relativistic electrons lose energy and radiate. The only suggestion of processes like these that might occur in white-dwarf stars has been the suggestion that mgnetic white-dwarf stars might produce the gamma-ray bursts (Chanmugam 1974, Mullan 1976).

III. INTERPRETATION OF INDIVIDUAL OBJECTS

Thus there are a variety of processes that can produce radiation at short wavelengths. The first step in any theoretical analysis is discovering which process is at work in an individual star, and then analyzing the results. As you progress down the electromagnetic spectrum, the processes increase in characteristic temperature, and distance from the traditional arena of stellar physics - stellar photospheres. Consequently the different spectral regions will be treated in order.

The Ultraviolet Spectral Region

Radiation from white-dwarf stars in this spectral range (here defined as from 911 A to the atmospheric limit at about 3000 A) comes from stellar photospheres. As a result, the time-tested techniques of model-atmosphere analysis can be used in the interpretation of the available observations of single stars.

The characteristic parameters of a stellar atmosphere are T(eff) and log g. Wesselius and Koester (1978) used broad-band observations from the ANS satellite to determine T(eff) for 10 stars, and Greenstein and Oke (1979) used higher resolution observations from the IUE satellite in a similar venture. The findings were that values of T(eff) determined from ground-based work by Shipman (1972, 1977b, 1979), Greenstein and Sargent (1974), and Schulz (1977; see Koester et al. 1979b) were in general extremely good. The values in Shipman (1972) for the hot stars HZ 43 and Feige 24 were in fact fortuitously close to those determined by the ultraviolet observers. These results are an important check on the analyses of Koester et al. (1979) and Shipman (1979) of white-dwarf radii.

However, if the ultraviolet region is to provide new, significantly better values of T(eff) and hence more accurate radii for stars with parallaxes, significantly improved photometric precision is required. Although the slope of a color- T(eff) relation is considerably greater when color indices that span the ultraviolet and visible spectral regions are used as temperature indicators,the limited photometric accuracy (both relative and absolute) that is so far available leads to errors in temperatures that are comparable to the errors given for temperatures determined solely from optical data. Specifically, my unpublished models show that the color index (uv-v), defined as -2.5 log (f(1500 A)/f(5420 A) is fit within 0.3 mag by the relation (uv-v) = -3.674 + 58.953(1/(T/1000 K)). The comparable fit for the color index (u-v) (Greenstein 1976) is (u-v) = -1.164 + 20.799(1/(T/1000 K)). Thus, with the same error in the two color indices, ultraviolet photometry should provide effective temperatures with three times the precision that the visible spectral range has. However, the relative and absolute calibrations of ultraviolet photometry are about three times worse than the errors in the visible, and the derived uncertainties in T(eff) are comparable. If the needed precision can be obtained, the determinations of stellar radii such as those by Koester et al. (1979) and Shipman (1979) could be redone. Such precision might help settle the one disagreement between my work (Shipman 1977b,1979; Shipman and Sass 1980) and the parallel investigations of the Kiel group (Weidemann 1977b, Koester et al. 1979b)-- the width of the white-dwarf mass distribution. In addition, the ultraviolet region can be used to determine temperatures for very hot stars like Feige 24 and HZ 43. These stars are so hot that the visible spectral region provides very few diagnostics. While the radius of each of these objects is very insensitive to the temperature adopted, the correct interpretation of the EUV flux does benefit greatly from a precise value of T(eff).

Probably the bulk of new information arising from observations of normal, single white-dwarf stars in the ultraviolet will arise from the determination of the abundances of various species of chemical elements. There has been a revival of interest in the origins of the curious chemical composition of white-dwarf atmospheres, highlighted by a flurry of theoretical papers (Fontaine and Michaud 1979; Vauclair, Vauclair, and Greenstein 1979; d'Antona and Mazzitelli 1979). Observations to date (Greenstein,private communication; see his paper in this volume) show lines of He II, C IV, N V, Mg II, Si I and IV, and Fe II in various stars over a wide temperature range. Most of these elements can be only probed weakly (if at all) by optical observations. As a result, analyses of the ultraviolet observations should provide significant new information regarding the chemical evolution of white-dwarf atmospheres. Analyses of the hot white dwarfs which show both H and He in their spectra (Koester et al. 1979a) should provide some extremely interesting insights.

Objective-prism surveys of the sky done by the Skylab S-019 experiment and the few ultraviolet sky surveys that have been done so far have produced some additions to the list of known white-dwarf stars. Several stars were shown to have companions which were surprisingly bright in the ultraviolet, and further investigation has indicated that in one case at least this companion, HD 149499 B, was a white dwarf (Parsons et al. 1976a, Wegner 1979a). another object, a pre-white dwarf, subdwarf, or possible white dwarf, was reported by Parsons et al. (1976b). Now that the sample of spectroscopically confirmed white-dwarf stars contains well over five hundred stars, the discovery of a few more does not, at first , seem to provide much new information. However, one of the stars discovered by the S-019 experiment, HD 149499B, may well be the only pure He hot star. Further, an outstanding uncertainty in estimating the number of white-dwarf stars in the Galaxy is the need to estimate the number that are hidden in binary systems (Liebert 1978); it may be that these ultraviolet surveys will provide some useful information on that line. Finally, an ultraviolet, EUV, or X-ray survey will provide information on the number density of extremely hot white dwarfs. The cooling rate, and hence the number density, of these objects depends on the rate at which neutrinos can cool stars when they are at the hottest part of the pre-white dwarf evolutionary track (see Savedoff et al. 1969; the most recent determination of the expected number densities is by Koester 1978). Thus a count of the number of hot white dwarfs would provide indirect information on weak-interaction theory.

The Extreme Ultraviolet (EUV)

This spectral region, here defined as 100-911 A, was the last part of the electromagnetic spectrum to be explored. An EUV telescope on the Apollo-Soyuz mission discovered a number of EUV emitting objects, two of which are the hot white dwarfs HZ 43 (Lampton et al. 1976) and Feige 24 (Margon et al. 1976c). Analysis of the radiation from these two stars has provided a new diagnostic tool for determining the properties of white-dwarf surface layers. What can be learned from the EUV?

The intensity of EUV emission from a white-dwarf star is an extremely steep function of the stellar temperature. However, accurate model atmospheres are necessary in order to make temperature determinations. The first T(eff) determinations for HZ 43 (Margon et al. 1976b, Durisen et al. 1976) exceeded 100,000 K. In one case a black body was used, and in the second, a helium- and metal-rich atmosphere, not transparent in the EUV, was used. Auer and Shipman (1976,1977) determined the effective temperature using helium-poor model atmospheres, consistent with the absence of any He features in the optical spectrum. Margon et al.(1976c),in the discovery paper for Feige 24, used a relatively primitive (not flux-constant) model atmosphere in their analysis;my own model atmospheres, which are subject to the constraint of flux constancy (equation 4) produce the same values for T(eff) that Margon et al. find.

From these investigations of HZ 43, Feige 24, and the x-ray flux from Sirius B, experience has shown that some caution is required. In interpreting measurements made with broad-band filters, it is essential to know the energy response of the filter accurately in order to fold the filter response with a stellar energy distribution that falls very steeply with increasing wavelength (see Figure 1). In addition, the temperature is only known as a function of the He abundance ,because the amount of He in the star and the interstellar column density of H can also affect the flux level in the EUV. Therefore, because the EUV data that are currently available can be fitted by various combinations of the parameters n(He), T(eff), and n (interstellar H I), data from the optical and ultraviolet regions of the spectrum can complement the EUV observations quite nicely.

Determining the temperature of a hot star is of interest because the maximum temperature of a white-dwarf star is determined by the rate of neutrino cooling. In addition, a precise value of T is required in order to see whether the spectral energy distribution of the star, which can now be measured from 10,000 A to 100 A, can be fit by a model photosphere. If no model can fit all the data, one of the other emission mechanisms discussed in section II must be appealed to. However, the radius of one of these hot stars is not really better determined by EUV observations, since the optical stellar flux is not very sensitive to T(eff) and thus the radius that you determine is not very dependent on T. So far, the radii for HZ 43 and Feige 24 seem reasonable (Shipman 1979). The mass of Feige 24 was also determined from analysis of the binary orbit, falling within the usual white-dwarf range (Thorstensen et al. 1979).

Take HZ 43, a star with a maximum amount of available data, as an example. Auer and Shipman (1976,1977) determined a variety of values for the parameters n(He), T(eff), and n (interstellar H I) that could fit the data. Recent pieces of information allow me to narrow the permissible parameters somewhat. Lick Observatory profiles (Margon and Shipman, in preparation) of the H lines indicate that a preferred temperature is near 60,000 K, and limit the He abundance at this temperature to 0.0001. This complements the observation of the He II 227 A edge by Malina et al. (1979), who find that n(He) is between 10^{-5} and 10^{-4}. The Auer and Shipman (1977) relation between T and n(He)/n(H), along with the temperature of 61,000 K determined from ultraviolet data by Wesselius and Koester (1979), gives a He/H ratio of 1.5 x 10^{-5} ,in good agreement with the results of Malina et al. Bleeker et al. (1978) have EUV/soft X-ray spectral information on HZ 43 in somewhat more detail than Margon et al. (1976) provide. Unfortunately the published flux levels in the soft X-ray region vary widely (Margon et al. 1976a,b, and references therein) and the interpretation of the data is as yet uncertain. Heise and Huizenga (1979) argue that the spectra require a layered model atmosphere, with a He subphotosphere and a H photosphere. Such an atmosphere may or may may not be stable. Additional work on this observation is required. A further possibility is that photoelectric absorption by C,N, or O may produce the flattening of the spectrum at low energies. To summarize the interpretations of the HZ 43 data, then, the available information (apart from the soft x-ray spectra of Bleeker et al.) is consistent with T(eff) = 60,000 K, He/H = a few x 10^{-5}, and n(interstellar H I) - approximately 0.01 atoms/cm^{-3}.

An idea of the amount of information on He abundances that can be obtained is provided by the data on Feige 24, the other EUV white dwarf detected by Apollo-Soyuz. It was not seen in the hardest Apollo-Soyuz band (Margon et al. 1976). Margon et al. interpreted this as showing that there are significant quantities of He in the atmosphere. My models indicate that $3 \times 10^{-5} < n(He) < 3 \times 10^{-3}$, using the same techniques as described in Auer and Shipman (1977).

The abundance of heavier elements, C,N, and O in particular, can be determined from more detailed EUV spectral information. These elements absorb at a variety of wavelengths between 500 A and 78 A. Auer and Shipman(1977) noted approximate upper limits of 0.001 times the solar value for these elements. The edges are detectable at the 5 % level with abundances of 0.0001 solar. Thus the EUV can provide additional information on the chemical composition of these hot objects. Because the EUV emitting white dwarfs are the youngest white dwarfs, they can provide insights on the time that the chemical evolution of white-dwarf atmospheres takes place.

An additional piece of information provided by the EUV observations is information on the interstellar medium. In order to be visible at all, an EUV emitter must be located in a direction where the H I column density is quite low. Column densities of 10^{18} cm^{-2} can provide significant EUV opacity and can thus be detected by EUV observations (Auer and Shipman 1977, Margon et al. 1976c, Cash et al. 1979, Shipman and Wegner 1979). In contrast, the Copernicus satellite can only detect column densities higher than 10^{19} cm^{-2} (Bohlin et al. 1978). Information provided by the EUV and ultraviolet is thus complementary in that the EUV can provide information on the ISM at distances ranging from tens to 100 pc and neutral hydrogen densities of the order of 10^{18}. cm^{-2}. The EUV observations so far indicate that there are several directions in which the number density n(H I) is approximately 0.01 cm^{-3}.

How many EUV-emitting white-dwarf stars do you expect to see? Koester (1978) provided some numbers, which I reproduce in Table 3 along with an estimate of their brightness at 320 A. Column 1 is a temperature, 2 the Eddington flux at 320 A, taken to be a representative EUV wavelength, and column 3 is the number of objects hotter than this T(eff) within 100 pc, based on Koester (1978) and including neutrino cooling. Column 4, based on my models, gives the brightness of an object with T = T(eff), assuming negligible interstellar absorption and placing the object 100 pc away (a bit further than HZ 43, which is 62 pc distant, with an interstellar optical depth of 0.1). The flux in column 4 is expressed in units such that the observed flux from HZ 43 would be 1.

Table 3

Densities and Brightnesses of Expected EUV White Dwarfs

T(eff)	H (320 A)	N with d< 100 pc and T>T(eff)	Flux at d = 100 pc
80,000	8.9(-3)	2.7	1.4
60,000	2.5(-3)	10	0.4
40,000	4. (-4)	47	0.06
35,000	5.8(-5)	92	0.01
30,000	3.4(-6)	180	0.0005

Table 3 shows that an EUV mission with considerably greater sensitivity than the Apollo-Soyuz project had could find many white-dwarf stars. Other objects that also emit in the EUV such as O and B subdwarfs and other types of stars (for example, the apparently normal B star HD 192273 that is probably a binary system; Wegner 1979a, Shipman and Wegner 1979; novae, and so forth) would increase the number of objects. The dwarf nova SS Cygni is an EUV source (Margon et al. 1978). The EUV radiation is apparently from a free-free emitter, and the optical radiation is interpreted as black body. But the model constraints are weak, and modeling of accretion related emission is not as well-developed as modeling of stellar atmospheres (see section II above).

X- and Gamma-Radiation from White Dwarfs

Information available so far is very scanty in this spectral range. Detection of large numbers of objects has only been possible with the launch of the Einstein satellite (HEAO-B), and none of this data has yet been published or analyzed. Objects definitely detected are HZ 43 in the soft x-ray region (see above), the magnetic white dwarf AM Her, and possibly Sco X-1 and Cyg X-2, though there is controversy regarding the nature of these objects (Katz 1977, Kylafis and Lamb 1979).

Thermal radiation from stellar photospheres will be primarily in the ultrasoft spectral region. The techniques of analysis and the insights to be expected parallel those of the EUV (see Auer and Shipman 1977 and the discussion above). Although the fraction of radiation emitted in this spectral range is low, even for very hot white dwarfs, the sensitivity of x-ray telescopes is such that many objects can be detected. We can expect to place more sensitive limits, or find positive detections, of abundances of light elements, and determine the role of neutrino cooling. Wesemael (1978) has found that existing background measurements indicate that neutrino cooling must take place; more data would indicate whether the current theories are the correct ones.

Coronal emission should be detectable by the HEAO-B satellite, which can detect stars with x-ray luminosities as low as 10^{26} ergs/sec (Giacconi 1979). If the predictions of coronal luminosities discussed above are anywhere near correct, virtually every He-rich white dwarf should be surrounded by an observable corona. It would be interesting to survey the emission-line objects to see whether they all have coronas.

Accretion-related processes are responsible for the most luminous x-ray sources. Various classes of objects have been detected with varying degrees of confidence. The most certain detection is that of AM Her; here the observations are interpreted in terms of a model with an accretion column (not a disk) falling onto the magnetic poles of the star (see the review by Angel 1978 and other papers in this volume). SS Cygni has been detected in outburst (Rappaport et al. 1974), though this detection may be statistically dubious (Robinson 1976). A third possible class of object is far more luminous and has undoubtedly been seen; the question is whether Sco X-1 and Cyg X-2 are white dwarfs. Further analysis and interpretation of these objects should lead to more insight regarding accretion disks, producing better understanding of other objects that produce energy by accretion (neutron stars and black holes). To date, no one has interpreted x-rays from white-dwarf stars as coming from high-energy processes involving relativistic electrons. If the gamma-ray bursters do turn out to be magnetic white dwarfs, then this type of emission process must also be considered in making models.

IV. THE ENIGMA OF SIRIUS B

Sirius B is the nearest, brightest, and most enigmatic of all the white-dwarf stars. Many new breakthroughs in the white-dwarf field have involved this star. You can seek to understand white-dwarf stars by analysis of large classes of objects or by intensive study of individual stars; the first approach has the advantage and disadvantage of obscuring any individual peculiarities. The advantage is that if one or two stars in the sample are very unusual, the overall result is not affected. However, one of our aims is the discovery of unusual objects and the elucidation of unusual phenomena.

In the last decade, a great deal of new observational data regarding Sirius B has become available. Greenstein, Oke, and Shipman (1971) measured the gravitational redshift, showing that Adams' (1925) spectra, the spectra that resulted in the classification of Sirius B as a white dwarf, were in fact hopelessly contaminated by scattered light from Sirius A. Thus this first indication that Sirius B was a hot object is, in retrospect, flawed. Mewe et al. (1975a,b) discovered x-rays from the system, and the interpretation of these is one of the most fascinating areas of study now. This discovery was confirmed by HEAO-1 observations of Lampton et al.(1979). HEAO-2 verified that most of the x-rays in the system were coming from Sirius B (Giacconi 1979) although more information may yet be forthcoming. In the EUV, Riegler and Garmire (1975), then Shipman et al.(1977), and then Cash et al.(1978) determined progressively stringent upper limits to the flux. In the ultraviolet, Savedoff et al. (1976) reported the detection of flux from the star in a very difficult observation from Copernicus. Brune et al. (1978) showed that the flux needed to be in the lower range of that detected by Savedoff et al. Böhm-Vitense, Dettmann, and Kapranidis (1979) detected Sirius B from the IUE satellite. Developments in the visible include Rakos and Havlen's (1977) photometry and the very precise parallax of Gatewood and Gatewood (1978).

With all these observations available, the theoretical interpretation of the x-ray flux is still unclear. Shipman (1976) showed that an unblanketed model atmosphere with T(eff) = 32,000 K could produce the required x-ray flux by thermal emission from the deep layers. This T(eff) for an unblanketed atmosphere corresponds to a value of T(eff) of about 30,000 K for a blanketed model, because the inclusion of line blanketing removes flux in the ultraviolet . An alternative source for the x-rays was the coronal proposal of Hearn and Mewe (1976). The ultraviolet and EUV observations, interpreted at face value, show that T(eff) cannot be high enough to produce the x-rays thermally (Cash et al. 1978; Brune et al. 1978; Böhm-Vitense et al. 1979). In addition, Koester (1979) shows that Rakos' photometry argues for a lower temperature of 22,500 K; my own models confirm this result, though I feel Koester's error is optimistic. Rakos' Stromgren u-v color would have to be 0.3 mag bluer to make Sirius B hot enough to produce the x-rays. While the observation of Sirius B is extremely difficult, the scatter in Rakos' three determinations of (u-y) is sigma = 0.07 magnitudes, one-quarter of the amount the colors would need to be wrong if the x-rays were to be thermal. I believe that the visible and ultraviolet data could be stretched to the limit to allow for a temperature high enough to produce the x-rays, but such stretching of the data requires some compelling reason.

However, the coronal model is not without its problems as well. A hydrogen atmosphere with T(eff) greater than approximately 12,000 K is convectively stable. Hearn and Mewe (1976) attempt to circumvent this problem by postulating a He subphotosphere. Fontaine (1977), in particular, questioned whether the necessary acoustic flux could be generated by a subphotosphere that was deep enough to be spectroscopically invisible. In view of the revised coronal energy requirements of Lampton and Mewe (1979) and the considerable uncertainties in coronal models in general (see section II above), this model may be just barely viable (see also d'Antona and Mazzitelli 1978). Another problem with the coronal model is that the HEAO-1 observation indicates that the x-rays are too soft to reconcile with the generally proposed coronal temperatures of 1-2 x 10^6 K (Lampton et al. 1979).

So where do we stand now? The question of the origin of the x-rays is not significant as far as the role of Sirius B as a benchmark in testing the mass-radius relation (Greenstein et al.(1971, Gatewood and Gatewood 1978), since the derived radius is relatively insensitive to temperature. However, one wants to know where the x-rays come from. There is, at present, no satisfactory answer. The outlook for the thermal model is not promising. The coronal model has the advantage that one can appeal to our greater ignorance of coronal phenomena when compared to our understanding of stellar photospheres. Right now, the coronal model does not fit current expectations of what coronas should be like. A helium subphotosphere must be invoked to heat the corona, and the HEAO-1 data shows that the spectrum is too soft and therefore that the corona is cooler than one would expect.

There are still more puzzles. Sirius B has a mass that is greater than that of the average white dwarf. Weidemann (1977a, Koester et al. 1979b) has suggested that it is atypical and that there has been mass exchange in the system. Lauterborn (1968) showed that it is possible to produce large-mass white dwarf stars after mass exchange and to end up with separations that are surprisingly large. His final model had a separation of 815 solar radii and a period of 2.3 years. However, the separation of the Sirius system varies from 1700 to 6800 solar radii, and so one cannot invoke Lauterborn's model to prove that mass exchange has taken place in the Sirius system. In addition, can a star be in an elliptical orbit after mass exchange has occurred?

Then there is the very intriguing question of whether Sirius was a red star in Ptolemy's time. The evidence for this goes far beyond one simple entry in Ptolemy's star catalogue; Brecher (1977) has provided a good summary of the various historical accounts. The lifetime of Sirius B as a normal white dwarf is far too long to allow for a normal evolutionary scenario (Lindenblad 1975, Shipman et al. 1977). Was there some kind of a pseudonova event at that time? Does that have anything to do with the x-rays? D'Antona and Mazzitelli (1978) think not. And then we have the most recent puzzle--the presence of a third, emission-line light source in the Sirius system--"Sirius C". This object, located about 6 arc-sec from Sirius B and 12 arcsec from Sirius A, was discovered by Böhm-Vitense from her IUE spectra and is reported on by Böhm-Vitense in this volume (see also Böhm-Vitense 1979). These multiple enigmas indicate that Sirius B, like the Crab Nebula and the Orion Nebula, will remain an interesting object for some considerable time to come.

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