HOT SUBLUMINOUS STARS

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1. SUMMARY AND INTRODUCTION

Extensive mass loss is observed for hot subluminous stars, through P Cygni lines in the ultraviolet. This persists in some subdwarf O stars, but is generally not observed in white dwarfs. The ultraviolet provides determination of effective temperatures. Among nine sdO's, the maximum temperature reported is definitely below 60,000 K; an object at 100,000 K would be distinguishable. The sdO's show a wide variety of line strengths, notably in N V, C IV and Si IV, as well as He II. One halo sdB is reported as rich in peculiar elements; it shows anomalous N V for its temperature. The comparison of effective temperatures of white dwarfs observed from space and from the ground gives excellent agreement. The hottest white dwarfs are near 60,000 K, although one (helium-rich) reaches 80,000 K. Another helium-rich close binary probably has an accretion disk; it is the only white dwarf to show the expanding shell of N V, C IV, Si IV characteristic of some subdwarfs. Two magnetic white dwarfs have been observed; one has strong unidentifiable features and the smallest known radius.

2. HOT, HIGH-LUMINOSITY STARS

From observing platforms in space, spectroscopic classification and luminosity criteria have been developed for stars of high luminosity and temperature. Not unexpectedly, an additional phenomena, the tendency to instability, has appeared. P Cygni profiles, of common, highly-ionized atoms appear with displaced multiple absorption components to -1500 km s^{-1}. The mass-loss rate increases with luminosity, reaching 10^{-6} to 10^{-4} $M_{\odot}$ yr^{-1} in Wolf-Rayet stars. Repeated Copernicus and high-resolution IUE observations are necessary (Wolf and Appenzeller 1979). Anne Underhill (e.g., 1979) has consistently urged the importance of stellar chromospheres and coronae even in stars where no convective driving force is expected. Massive binaries containing a Wolf-Rayet star display winds and streams (Willis et al. 1979; Willis and Wilson 1978) and relatively low temperatures, e.g., 30,000 K for

255

a WC8. Different ions have different expansion velocities (Conti and
van der Hucht 1979). The case is proved--high luminosity stars are
unstable, and their envelopes are detected at radio, infrared and
ultraviolet frequencies. What happens in single stars of lower lumi-
nosity at high temperature, and in binaries, either detached or inter-
acting? Oscillating β Cephei stars show distorted absorption pro-
files (Lesh 1978; Lesh and Wesselius 1979). Are there low-luminosity
analogs?

3.   WHAT IS A HOT LOW-LUMINOSITY STAR?

In single, halo or old, highly-evolved stars, high temperatures
appear at the left end of the horizontal branch, in stars of 1 $M_\odot$,
typically near 100 $L_\odot$. The surface gravity, g, enters through the
dimensional formula $L \propto MT^4 g^{-1}$; typical radii are 0.1 $R_\odot$ at temper-
atures near 60,000 K, log g $\approx$ 6. Such a star is a hot subdwarf, and
this group requires much further quantitative analysis, both from the
ground and space. We believe that sdO's extend downwards from the
nuclei of planetary nebulae (up to 10^4 $L_\odot$, 1 $R_\odot$, log g = 3), to near
the upper end of the hot white-dwarf sequence (log g = 8). Theoretical
importance attaches to questions such as: (1) How hot can a subdwarf
be? This involves the resulting high neutrino luminosity. (2) If the
temperature limit is below that of the nuclei of planetary nebulae,
which seems to be the case, why? Is it the continuing mass loss?
(3) Does a connection exist between the hot end of the globular-cluster
horizontal branch (the so-called sdB's) and the sdO's? Here, evolu-
tionary models suggest tracks leading to very high g. Ground-based
studies by the Kiel group (Hunger, Kudritzki) are underway. (4)
Finally, how hot do white dwarfs get, what are their spectra like and
why so different from those of sdO's? This involves us in the ques-
tion of the rapid separation of H or He from heavier elements, in
which white dwarfs differ so much from all other stars.

4.   HOT SUBDWARFS, sdO

These are notable for a variable but high He/H surface ratio,
probably surrounding a helium-carbon, contracting core. Parameters
for many in the halo are given by Greenstein and Sargent (1974),
log g = 4.0 to 6.5, T = 35,000 to 50,000 K. Non-LTE analysis by
Kudritzki and others (Kudritzki and Simon 1978; Simon et al. 1979;
Kudritzki 1976) of a single-line spectroscopic binary HD 49798, give
47,500 ± 2000 K, He/H = 0.5. Interactions in the close binary may
occur; the high-resolution IUE spectrum shows a strong N V P Cygni
line reaching -1500 km s^{-1}, and a mass-loss rate of 4 x 10^{-8} $M_\odot$ yr^{-1}.
The He II lines up to 3 → 9 (λ4686 series) fit theoretical profiles
for log g = 4.25. While slightly hotter sdO's are known, single,
higher g objects need study, to test whether the evolutionary tracks,
some of which reach 60 to 70,000 K are correct. Another sdO in a
binary studied by Darius and Whitelock (1978) is HD 17576; the TD1
colors give 42,000 K, and suggest a low luminosity and a surface
gravity near log g = 7.

Greenstein and Oke have studied 7 sdO's for which multichannel scans exist at low resolution with the IUE. Figure 1 shows the λ2500 region of GD 298, a high-latitude, He-rich object. The flux
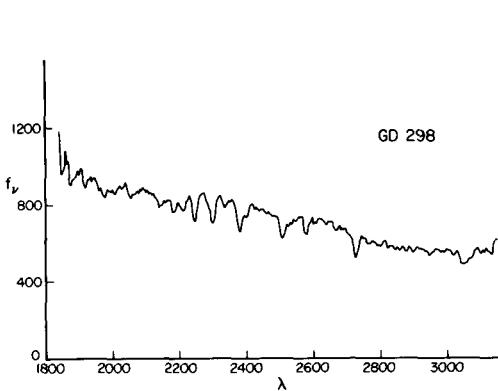

Figure 1. The λ2050, 3 → ∞ series limit as seen in a sdO, GD 298 near 40,000 K. We give $f_\nu(Hz)^{-1}$, as $f(\lambda)$. At shorter wavelengths, C IV absorption is strong.

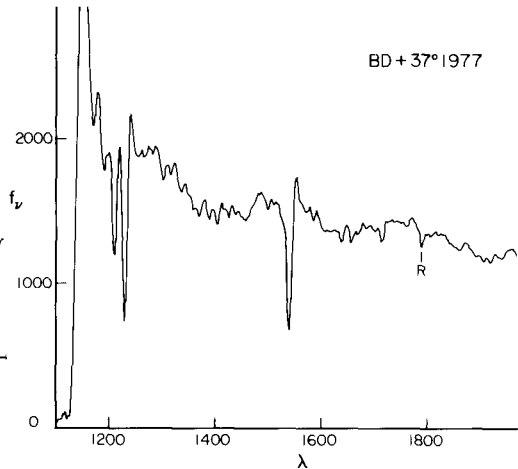Figure 2. The λλ1550,1240 P Cygni lines of C IV and N V in the sdO +37°1977; also seen is λ1215, but λ1640 of He II is weak.

distribution indicates 40,000 K and moderate g, since He II 3 → 10, 11 are seen; C IV is strong compared to He II 2 → 3, λ1640. The strange He-rich star +37°1977 (Fig. 2) has much stronger P Cygni lines of C IV and our strongest detected N V with weak Si IV and He II λ1640. However, the ultraviolet color temperature is anomalously low, 25,000-30,000 K but 40,000 K in the optical region. We have fitted models for these seven sdO's. The generalization can be made that the sdO's include a wide range of log g, have varying strengths of He/N/C/Si, and do not cover a large range of T. One of our bluest stars, in fact, shows only weak Lyman-α. While interstellar reddening could affect T determined by model fitting or blackbodies, these stars are all at high galactic latitude. The reddening is negligible, probably E(B-V)< +0.04, from the absence of the λ2200 anomaly in the interstellar extinction. We also face a small revision of IUE sensitivity factors by Bohlin et al. (1979), not here included. But if the 2σ accidental error of 6 percent in IUE sensitivity eventually becomes the limit to the systematic accuracy, useful spectrophotometric effective temperatures up to 100,000 K can be determined. So far, no such high temperature has been suggested for any sdO. We have derived effective temperatures from 30,000 to 60,000 K. In this group we find the He II 3 → series often present, with λ1640 moderate. The blend H + He II at λ1215 is not outstandingly strong; whether C IV and Si IV absorption is strong seems random, and sometimes C IV P Cygni emission is seen.

The line most prone to emission is N V, e.g., in +37°1977 (Fig. 2);
this may be strengthened when helium is doubly ionized, or when there
is non-thermal, far-ultraviolet flux.

5.   HALO STARS

The horizontal-branch B's and the sdB's are apparently bright,
cooler stars, some being observed with the IUE at high resolution.
So far only Feige 86 (at low resolution) has been published by Hack
(1979). Her higher resolution spectra confirm the existence of pecu-
liar elements Si, Mn, P, Fe, Ga, Hg and N V. The interest in such stars
is that they extend to higher T the properties of the "peculiar" B.
Like them, the HBB and sdB appear He-poor; our low resolution IUE
spectra confirm the ground-based temperature scale showing, e.g.,
that Feige 66, a sdB with peculiar abundances, fits a 32,000 K model
well. Hack's observations of N V in Feige 86, which has several dis-
placed components, extends the sdO mass loss phenomenon to lower T;
since He II exists, the ionization may be from a non-thermal source,
or else T is much higher than expected.

6.   THE WHITE DWARFS

Since we now measure fluxes from 11,000 to 1150 Å (e.g.,
Greenstein and Oke 1979), we have an excellent opportunity to search
white dwarfs for the types of peculiarity found in the lower g stars.
The IUE calibration we used agrees with the ANS filter photometry of
hydrogen-rich (DA) stars by Wesselius and Koester (1979). We find
that our rough Lyman-α profiles also match theoretical, pure H models.
The most satisfying result is in Figure 3, a comparison of T_{eff} from
models fitted to IUE data alone, and to ground-based spectrophotometry.
The systematic agreement is perfect and accidental errors are 5 per-
cent; the hottest DA's are 60,000 K. This includes a log g = 8 DA
rapid variable, of the ZZ Ceti type; these are non-radial pulsators
in a high mode, near the extension of the Cepheid instability strip.
No ultraviolet peculiarity is seen in this ZZ Ceti star. No metallic
lines whatever have been detected in the 8 hydrogen white dwarfs--com-
pletely unlike sdO's or high-luminosity stars. The metals have van-
ished.

A very exciting chapter is opened when we turn to the newly dis-
covered object, the helium white dwarf discovered by Parsons et al.
(1976), observed with the IUE by Wray et al. (1979), possibly the
hottest subluminous star known, HD 149499B, about 80,000 K. How hot
are the Apollo-Soyuz, EUV white dwarfs, Feige 24, HZ 43? No evidence
for T > 60,000 exists, given that the atmosphere of HZ43 is so
transparent. The detection of the He II series limit (Malina 1979;
Bowyers 1979) by a rocket flight, shows He/H to be 10^{-4} to 10^{-5}. This
was required to explain the EUV detection by model-fitting of a thermal
source. I have studiously avoided the question of white dwarf coronae
or chromospheres. There seems little doubt that Sirius B, a DA at
27,000 K, is an X-ray source, and cannot be thermal, and 40 Eri B may
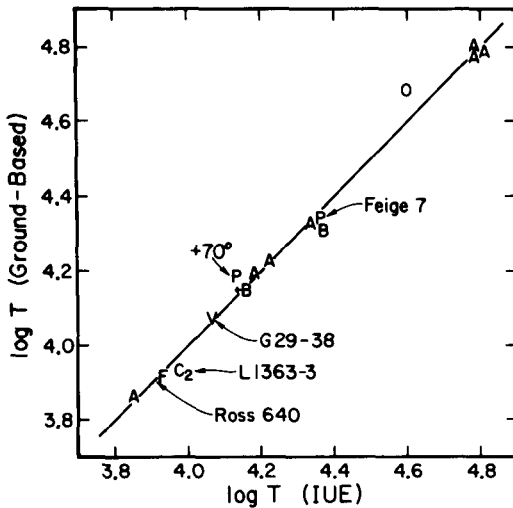be a source. In fact, nearly all the hottest white dwarfs are members

Figure 3. A comparison of white-dwarf effective temperatures determined with IUE and from the multichannel scans, mostly using model atmospheres. Symbols spectral types, V = variable, P - polarized (magnetic). No systematic scale difference can be detected.

of visual or spectroscopic binaries--a list being given in my Rochester Colloquium talk. They fit thermal spectra, however. No single white white dwarf has emission lines; apparently at $\log g = 8$, stars settle down, perhaps not unexpectedly, given the 6000 km s^{-1} velocity of escape.

    For the astrophysics of degenerate stars the UV observations of helium-atmospheres have been most stimulating. One in four white dwarfs have helium-dominated atmospheres. Note the extreme chemical purity of the DA's, where He/H = 10^{-5} to 10^{-4}, and no metals are seen. The DB's, however, have He/H = 10^5 to 10^4, somewhat less for the few known DBA composite atmospheres. But these helium stars often show metals. Certainly the Parsons et al. object is hot enough to show N V or C IV--but does not do so. We observed a DB star, GD 190 (which fits a He model), a cooler one, GD 40, with Mg II, and finally the rapid variable, HZ 29, AMCVn, type DBp, almost certainly a binary containing two helium stars. In HZ 29 we find enormous N V, He II, C IV, Si II absorptions, which are shifted to -1000 km s^{-1}. Here we must suspect mass exchange and accretion, with an f_ν = constant spectrum. Helium becomes fully ionized at 75,000 K (log g = 8), but HZ 29, at longer wavelengths fits a 24,000 K model, i.e., would lack far UV photons. Accretion may supply the photons of 75 eV to produce N V; and in HZ 29, we see the violet-shifted traces of mass being lost to the entire system, reminding us once more of the dynamic gas in stars of lower gravity.

7. MAGNETIC STARS

The continuum-polarized, magnetic white dwarfs will undoubtedly offer the widest variety of new phenomena, but not, apparently, hydrodynamical instability. They are faint, and will prove difficult, to observe, especially those with high fields (200 megagauss). Feige 7 (Fig. 4), has a mixed H and He atmosphere and shows Zeeman-resolved
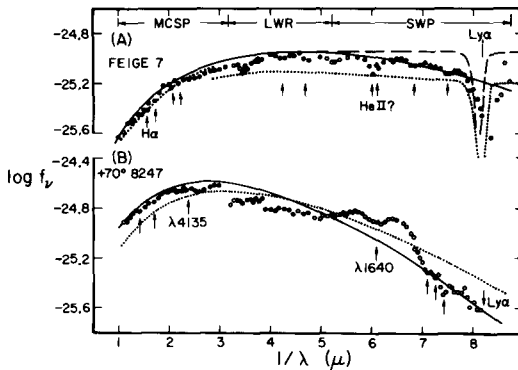

Figure 4. Monochromatic fluxes f_ν, for two magnetic white dwarfs. The models fit Feige 7 with a high He/H ratio, and predict the observed Lyman-α absorption. The strange, unidentified, spectrum of Grw +70°8247 cannot be modeled; two blackbodies at 16,000 and 14,000 K are shown. Arrows indicate probably real features. The total bolometric luminosity is well determined by the MCSP and IUE observations.

H and He I. The theoretical mixed atmosphere predicts the strong observed Lyman-α, in an object that optically has otherwise weak lines. The most fascinating and puzzling object is Grw +70°8247, the first white dwarf to have shown a polarized continuum. No optical features have been certainly identified; Angel (1979) suggests hydrogen transitions in a very strong field. The UV is full of undecipherable information; some sharp drops appear real, as is the great drop cutting off the spectrum at λ1400. No model could fit this, and if Lyman-α is involved, the broadening is many times larger than in any DA. A group of C I resonance lines exists in this region. We observe almost the entire energy output, i.e., the bolometric flux; with the accurate Naval Observatory parallax, the bolometric luminosity is known. Assuming that there is no synchrotron radiation, we determine the best-fitting blackbody--by least squares--T = 15,000 K, between the curves shown in Figure 4. Any blackbody is a poor fit, but we derive the radius as 0.6 percent of the sun--half the normal value. This is the smallest white-dwarf radius known, corresponding to 1.2 $M_\odot$, far larger than Sirius B.

We have gotten so far, but so much more remains to be done with a 45 cm telescope! This work was supported in part by NASA under

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DISCUSSION:

A.B. Underhill: In the O and early B-type supergiants the C IV resonance lines at 1548 and 1550 Å form a typical P-Cygni profile indicating the rapid outflow of a wind at high electron temperature. In B8 and B9 Ia stars these lines are weak, if present at all and the outflow velocity is near 200 km s^{-1}. Here I present the spectrum near 1550 Å of HD 21 389 = HR 1040, A0 Ia. There are moderately strong absorption lines due to Fe III and possibly there is very weak absorption due to C IV. The striking thing is the presence of sharp, essentially undisplaced emission components of C IV as in late-type supergiants. These lines vary in intensity; they are strong on one of my IUE high-resolution spectra, weak on two spectra and barely visible on the fourth spectrum. This observation demonstrates that in the outer atmosphere of HD 21 389 (A0 Ia), there is a highly ionized, hot region as in the G and K type supergiants. The changeover from hot rapidly flowing highly ionized winds to hot-slowly flowing winds seems to occur near A0 Ia. Cool gas flowing at a speed near 200 km/sec is seen by means of the Mg II resonance lines in the case of HD 21 389. A two-component wind may be present for this A0 Ia star.

J. Darius: With regard to the seeming discrepancy between the temperatures of hot field subdwarfs and those of central stars of planetary nebulae, may I comment that Jack Giddings of Professor Wilson's group at University College London has analyzed He I line profiles of BD + 37$^{\rm O}$ 1977 in the visible region and obtained $T_{eff} \gtrsim$ 50 000 K, considerably in excess of the value suggested by Dr. Greenstein.

J. Greenstein: We realize that this had the most discrepant ultraviolet flux, compared with that predicted from our optical scans and model fitting. We intend to reobserve it with the IUE; a difference 40 000 to 25 000 is unacceptable, or physically important.