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HUBBLE SPACE TELESCOPE STUDIES OF EXPOSED WHITE DWARFS IN DWARF NOVAE

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Abstract

Coordinated AAVSO optical observations and Hubble Space Telescope (HST) far ultraviolet (UV) spectroscopic observations of cataclysmic variables, during dwarf nova quiescence when the underlying white dwarf is exposed in the far UV, have yielded a number of new insights into accretional heating, photospheric abundances of the accreted atmosphere, and rotational velocities of the underlying degenerates. Recent results of synthetic spectral analyses of HST spectra are highlighted. Their impact on our understanding of accretion physics and the effect of accretion on the white dwarf are discussed.

1. Introduction

Dwarf novae are mass-transferring explosive close binaries consisting of a Roche lobe-filling solar-like dwarf star and an extremely dense white dwarf star in binary orbit, with orbital periods ranging from 1.3 hours to several hours. The white dwarf star accretes matter from a swirling pancake-shaped gas disk called an accretion disk. This disk forms because the gas stream leaving the solar-like star at the inner langrangian point has high angular momentum, and collides supersonically into the edge of the disk. As mass transfer builds up the disk, its surface density reaches a critical value which triggers an instability, causing the disk to fall onto the white dwarf. The release of gravitational potential energy (amounting to $\sim 10^{40}$ ergs!) during this episode of very high accretion is identified with the dwarf nova explosion. Eventually, the white dwarf will have accreted up to 10^{-4} $M_\odot$, at which time a second type of explosion, 10^4 more energetic than the dwarf nova, occurs due to unstable thermonuclear ignition of the accreted H-rich envelope. This explosion is identified as the classical nova. Although the center of action in both types of explosions is the accreting white dwarf, the physics of the accretion process onto the white dwarf remains poorly understood, chiefly because this dense compact star is hidden by the accretion disk. However, in a few dwarf novae, during the quiescent interval between outbursts the underlying white dwarf stars are exposed and dominate the far UV light.

Before the launch of the Hubble Space Telescope (HST), far ultraviolet spectroscopic observations of dwarf novae during quiescence, obtained with the Short Wavelength Prime Camera on the International Ultraviolet Explorer (IUE), had provided convincing evidence that the dominant source of light in the far ultraviolet wavelength region (1200–2000Å) of many (if not all) of these cataclysmic variable (CV) systems appears to be the white dwarf photosphere (e.g., Panek and Holm 1984; Mateo and Szkody 1984; Kiplinger *et al.* 1991). The white dwarf detection was mostly based upon the presence of the Lyman-α absorption line arising from the ground state of hydrogen and broadened by the enormous atmospheric pressure. However, the detection of other white dwarf spectral features and detailed synthetic spectral analyses of these faint objects while they are exposed during quiescence had to await the launch of HST. Even then, the HST observations would not be possible without the critical, continuous AAVSO optical monitoring, which establishes the onset and duration of quiescence. This paper describes the progress of ongoing coordinated AAVSO-Hubble Space Telescope investigations of the exposed white dwarfs during dwarf nova quiescence.

1. 1 Measurements of white dwarf heating/cooling in response to dwarf nova accretion events

In many dwarf novae, a decrease in the far UV flux during quiescence is observed. If this decline were due to a decrease in flux from the accretion disk it would contradict the standard disk instability theory, which predicts the disk should brighten through the quiescent interval because the accretion rate is gradually increasing. However, these flux declines could be accounted for if they are due to cooling of the white dwarf in response to the dwarf nova accretion event. HST observations of three systems have provided conclusive evidence of white dwarf cooling in response to the accretion event.

Upon notification by AAVSO observers that U Gem had returned to optical quiescence, Long *et al.* (1994) observed U Gem twice during the same quiescence with HST/Faint Object Spectrograph (FOS) at 13 days and 70 days after a normal dwarf nova outburst. They found a flux decline of 28% between the two observations, and that the white dwarf had cooled from 39,400K down to 32,100K between the two observations. In WZ Sge, the dwarf nova with the longest interoutburst time, the temperature of the white dwarf just after the December, 1980, outburst was 30,000K (Holm 1988). Since then the white dwarf surface temperature has been declining and had cooled to 12,500K in 1989 (LaDous 1991), based upon IUE measurements. More recently, HST/FOS spectra obtained 15 years after WZ Sge's 1978 outburst reveal that the white dwarf is roughly 3000K hotter (Sion *et al.* 1995a).

1.2 HST photospheric analyses of the exposed white dwarfs in U Geminorum, VW Hydri, and WZ Sagittae

The three CV systems we have observed to date with HST (VW Hyi, WZ Sge, and U Gem) represent ideal laboratories for exploring the physics of the interaction between the accreting disk gas and the white dwarf surface layers because their accretion rates are extremely low during quiescence, and their underlying white dwarfs not only dominate the system's light in the far UV, but also exhibit a clear UV turnover associated with the very broad Lyman-α absorption wing. Principal results achieved up to the present are summarized below.

1.2.1. U Geminorum

In addition to the FOS study of the cooling of the white dwarf during quiescence by Long *et al.* (1994), a pilot high resolution Goddard High Resolution Spectrograph (GHRS) study seeking the white dwarf rotation rate was also carried out. AAVSO observers had reported the end of a wide U Gem outburst, at which time Sion *et al.* (1994) obtained a pair of consecutive far ultraviolet GHRS exposures of the Si IV region in early quiescence on September 25, 1993, only 8 days after the AAVSO notification. Their observation revealed a fully resolved line profile for the resonance doublet of Si IV. The two spectra occurred at mid-exposure orbital phase 0.67 and at phase 0.87. The Si IV profile in the second observation is clearly redshifted relative to the first spectrum, due to orbital motion. If the profiles are associated with the white dwarf photosphere, then the best synthetic fits are consistent with $T_{\rm eff}$ = 35,000K–38,000K, log g = 8 (surface gravitational acceleration, $g = 10^8$ cm/s^2), a rotational velocity of 50 to 100 km/s, with a modestly enhanced silicon abundance (1.3–2.3 times the solar abundance of Si). These results (displayed in Figure 1) suggest that at least in U Gem and perhaps in other similar dwarf novae, the missing ultra-high temperature boundary layer cannot be explained by rapid rotation of the white dwarf. Unfortunately, the γ-velocity (i.e., the center of mass

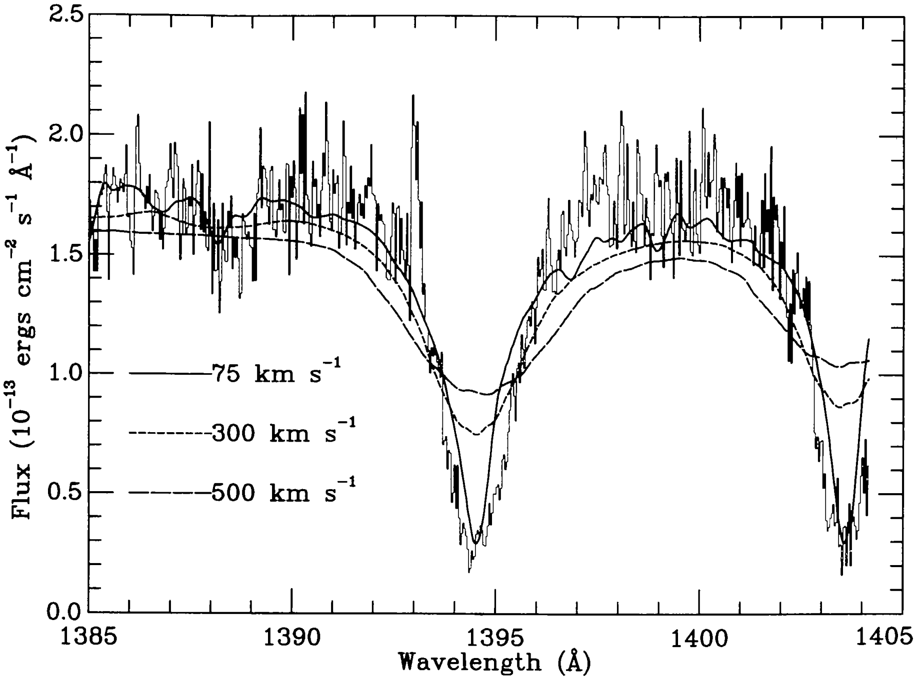

Figure 1. The Si IV resonance doublet absorption lines in U Gem fitted with model atmospheres with T_{eff} = 35,000K, log g = 8, and the indicated velocities.

velocity) of the system remains uncertain. If the γ–velocity is 43 km/s (Friend *et al.* 1990), then a gravitational redshift of ~50–60 km/s is implied for the white dwarf. If the γ-velocity is 84 km/s (Wade 1981), then a gravitational redshift of only 10–30 km/s is indicated, which may imply that either the white dwarf has a low (0.5–0.6 $M_{\odot}$) mass, or an extended atmosphere bloated by the outburst 8 days earlier. Further GHRS observations of U Gem during cycle 4 of HST should remove this uncertainty.

In order to rule out a rapidly spinning accretion belt, a comparison was made between the observed Si IV profile and models in which a portion of the white dwarf surface is assumed to be hot (60,000K) and rotating with V sin *i* of 5000 km/s. As the fraction of the surface rotating at high velocity increases, the fits grow worse because Si IV is weak at 60,000K (compared to 35,000K) and because of the very large Doppler width at this rotational velocity.

1.2.2. WZ Sagittae

Sion *et al.* (1995a) analyzed two consecutive HST/FOS spectra of the exposed white dwarf in the ultra-short period, high amplitude, dwarf nova WZ Sge. Their spectra revealed a rich absorption line spectrum of neutral carbon and ionized metals, the pressure-broadened Lyman-α absorption wing, the H_2 quasi-molecular Lyman-α "satellite" absorption line, and a double-peaked C IV emission line which is variable with orbital phase. The dominance of C I features confirms the identification of C I first reported with low resolution IUE spectra by Sion *et al.* (1991). The present spectral type of the white dwarf is DAQZ3. A synthetic spectral analysis of the white dwarf yields T_{eff} = 14,900K ± 250K, log g = 8.0. The best fit is shown in Figure 2. In order to fit the strongest C I absorption lines and account for the weakness of the silicon absorption lines, the abundance of carbon in the photosphere must be about 0.5 solar, silicon abundance is 0.005 solar, with all other metal species appearing to be 0.1 to 0.001 times solar. The H_2 quasi-molecular absorption is fitted very successfully.

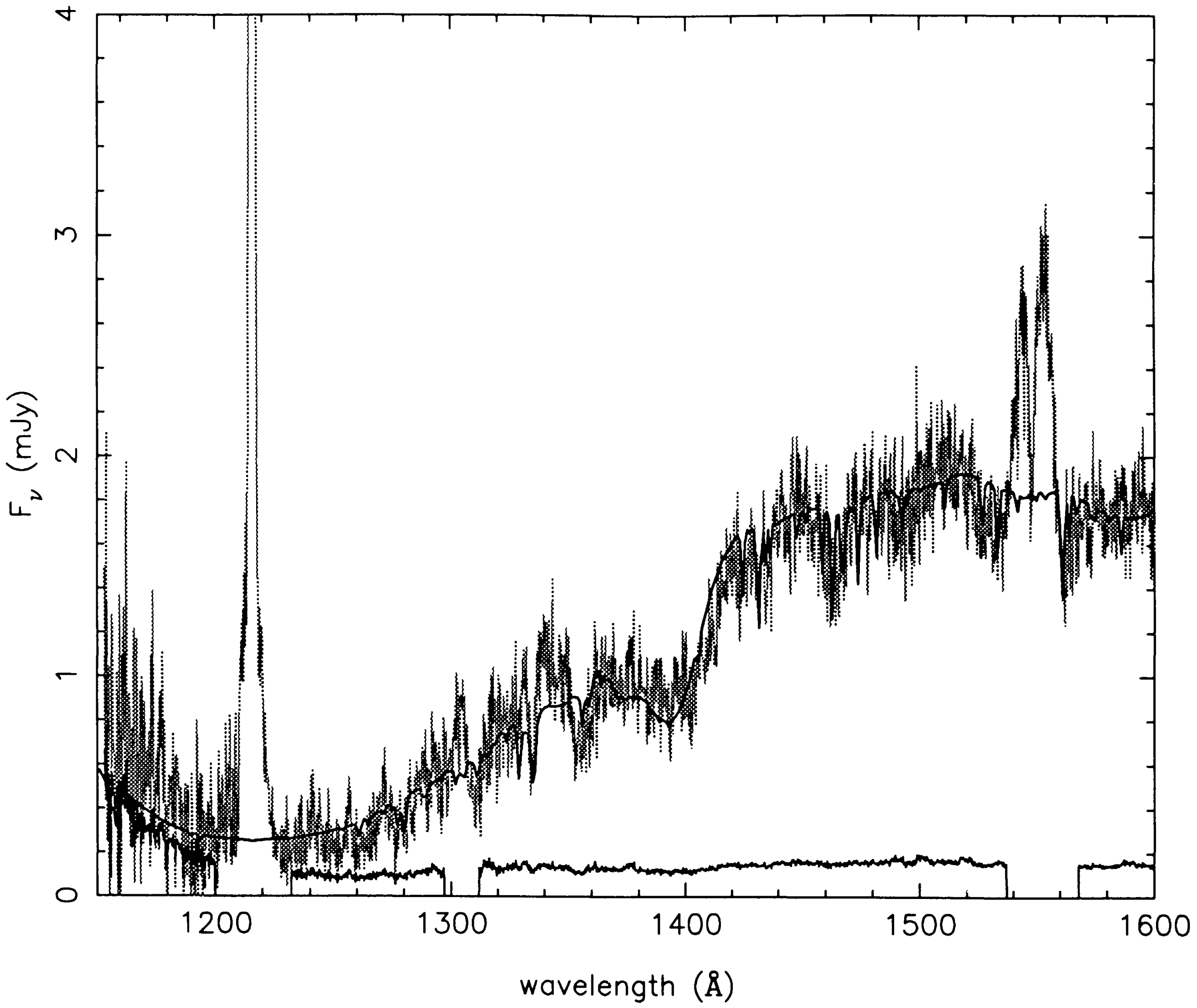

Figure 2. The best-fitting ($\chi^2 = 1.51$) synthetic spectrum to the summed data for the two FOS spectra of WZ Sge. The error bars of the summed data are shown at the bottom. The three gaps in the error bar curve indicate the wavelength regions masked in the spectral fitting. Note the broad Lyman-α H_2 quasi-molecular absorption at 1400Å, the rich absorption line spectrum, the emission at 1300Å, the double-peaked emission feature at C IV (1550Å) and its large variation in central absorption, and the Stark-Broadened Lyman-α longward absorption wing. The emission at Lyman-α is geocoronal in origin. The physical parameters are $T_{eff} = 14{,}900$ K, log g = 8, with carbon being the most abundant metal constituent in the hydrogen-rich atmosphere (Sion *et al.* 1995a).

Due to the extremely high gravitational field of the white dwarf, the photospheric metals sink deep into the white dwarf on timescales of fractions of a year. Therefore, they must have been accreted long after the 1978 December outburst. The source of the most abundant metal, carbon, is considered. If the time-averaged accretion rate during quiescence is low enough for diffusion (sinking) to be in balance with accretion, then the accretion rate of neutral carbon is such that it sinks at the same rate 7×10^{-16} $M_\odot$/yr, and the total accretion rate is 2×10^{-12} $M_\odot$/yr. However, our derived concentration of carbon is also consistent with the theoretically predicted amount of core carbon that convective gas bubbles could bring up to the surface from deep in the white dwarf's

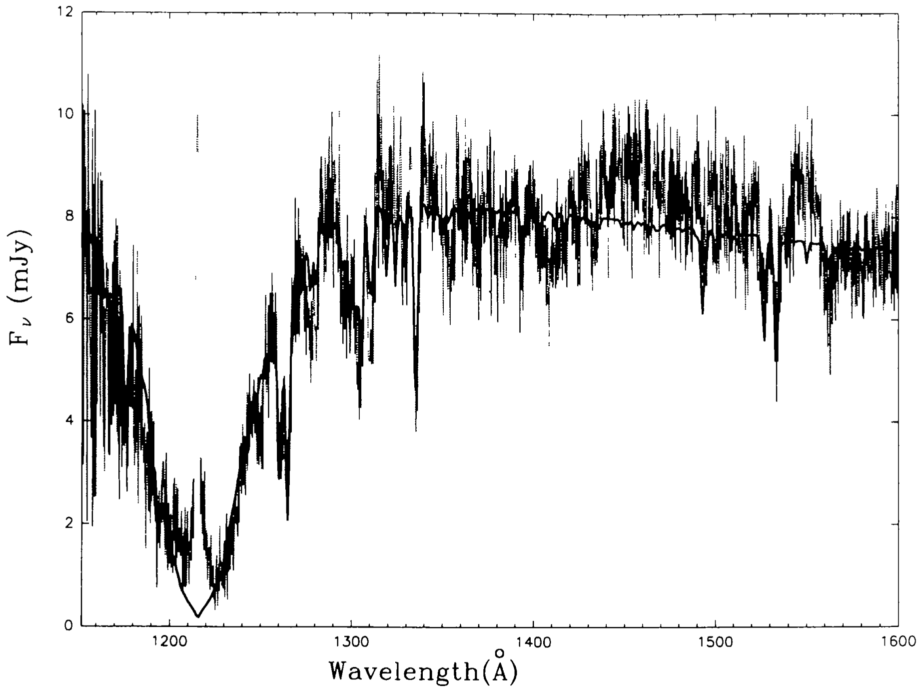

Figure 3. The model fit to the FOS spectrum of VW Hyi. The best-fit summed data for the two sub-exposures is shown. Note the very broad Stark-broadened Lyman-α absorption with narrow airglow emission, the rich metallic absorption line spectrum dominated by strong lines of Si II, Si III, C II, and C III.

envelope. This process does occur in single white dwarfs which are helium-rich, but it may also be possible in a hydrogen-rich star as in WZ Sge. Perhaps some other factor such as binary membership (e.g., rotation) impedes the rapid diffusion of C expected in a single degenerate.

1.2.3. VW Hydri

In an HST/FOS study of the cooling of the white dwarf in the dwarf nova VW Hyi, Sion *et al.* (1995b) analyzed a far ultraviolet spectrum of the dwarf nova VW Hyi, but a scheduling problem delayed the acquisition of the required second observation. The single observation occurred 10 days after AAVSO observers notified us of the return to optical quiescence from a superoutburst of VW Hyi (see Figure 3). The spectrum reveals a very strong Stark-broadened Lyman-α absorption with narrow geocoronal emission, and a very rich metallic absorption line spectrum dominated by strong ground state absorption features of singly and doubly ionized silicon and carbon, the first solid identification of metallic absorption features arising in the accreted atmosphere of the white dwarf. They confirm the reported low resolution IUE detection of the underlying white dwarf photosphere by Mateo and Szkody (1984). A synthetic spectral analysis with hot, high gravity in local thermodynamic equilibrium (LTE) model atmospheres yields a best fit model with the following parameters: $T_{eff} = 22{,}000K \pm 1000K$, $\log g = 8 \pm 0.3$, with chemical abundances of Oxygen = 0.3 times solar, Nitrogen = 5 times solar, and all other heavy elements = 0.15 times solar (see Figure 3). Based upon their absorption line measurements in the subexposures at different orbital phases, they find no conclusive evidence of equivalent width variations versus orbital phase. The phase. The elevation of the white dwarf surface temperature relative to previous largely IUE-based estimates of T_{eff} (18,000–20,000K) could be due to the placement of our FOS observation so close to the end of a VW Hyi superoutburst. In the absence of any significant reduction of the white dwarf's core mass by past nova explosions (which would make the white dwarf expand and therefore cool), its minimum age since formation (its so-called cooling age) is approximately 50 million years.

A first attempt to determine the rotation rate of the white dwarf in VW Hyi was carried out with the Hubble GHRS by Sion *et al.* (1994) They obtained a far ultraviolet spectrum in dwarf nova quiescence, covering the region of the Si IV (1393, 1402Å) resonance doublet. The broad, shallow Si IV doublet feature is fully resolved, has a total equivalent width of 2.8Å, and is the first metal absorption feature to be clearly detected in the exposed white dwarf. The synthetic spectral analysis, using a model grid constructed with the code TLUSTY (Hubeny 1988), resulted in a reasonable fit to a white dwarf photosphere with $T_{eff} = 22,000 \pm 2000$K, $\log g = 7.5 \pm 0.3$, an approximately solar Si/H abundance, and a rotational velocity $V \sin i \simeq 600$ km/s (see Figure 4). This rotation rate, while not definitive because it is based upon just one spectral line transition, is 20% of the Keplerian (breakup) velocity and hence does not account for the unexpectedly low boundary layer luminosity inferred from the soft X-ray/EUV bands (van der Woerd and Heise 1987; Belloni *et al.* 1991; Mauche *et al.* 1991, 1993), where most of the boundary layer luminosity should be radiated.

If the boundary layer (bl) area is equal to the surface area of the white dwarf, then $T_{bl} = 24,000$K. These values are essentially identical to the photospheric luminosity and temperature determined in far ultraviolet photospheric analyses. If the boundary layer area is 10^{-3} of the white dwarf surface area, then $T_{bl} = 136,000$K. A preliminary conclusion based upon this single line measurement of rotation is that the significant under-luminosity of the VW Hyi boundary layer compared to the disk cannot be explained by rapid rotation of the white dwarf.

2. Discussion

As a result of close cooperation with the AAVSO network of observers, the large mirror of HST has led to the emergence of new breakthroughs on several fronts regarding accretion from a disk into the equatorial regions of the white dwarfs in non-magnetic cataclysmic systems: (a) the first rotational velocities for the underlying white dwarfs in cataclysmic variables; (b) the first white dwarf masses independent of disk emission lines; (c) the first chemical abundances for accreted atmospheres; (d) the first definitive evidence of white dwarf cooling in response to the dwarf nova accretion heating process in several systems. With the prospect of more high quality HST spectra on other CV systems and a growing HST archive, the stage is now set for further unprecedented detail on the structure of CV boundary layers, the diffusion and mixing of the accreted disk material, the white dwarf surface area and depth through which the accreted matter spreads or shear mixes, and the detailed budget of the accretion energy. These developments will surely help to understand the detailed breakdown of the accretion energy budget, the true accretion geometry, how extensively the white dwarfs are heated with latitude and with depth, why some systems have wind outflow during their outburst or high accretion phases, and the ultimate evolutionary effect of inward energy flow on the underlying white dwarf's evolution.

The enormous complexity of the Hubble Space Telescope scheduling pipeline yields a slower response time to target-of-opportunity observations than smaller spacecraft observatories. Thus, the only possible way to achieve the above objectives on accretion physics and its effects on the exposed white dwarfs is to have the continuous closely coordinated optical monitoring provided by the AAVSO.

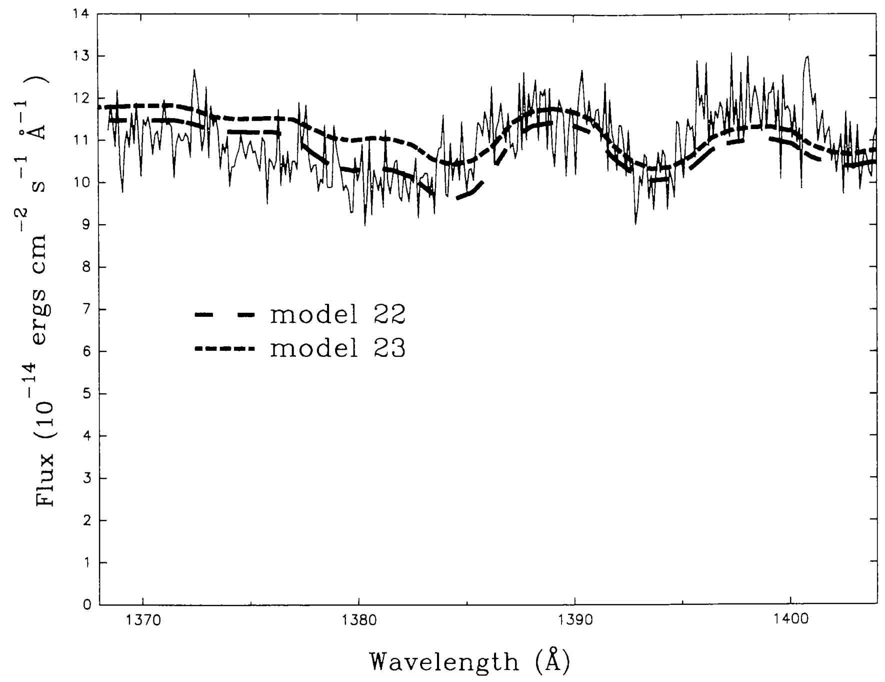

Figure 4. A comparison between the observed GHRS spectrum of Si IV region and model fits to the region. The best fit white dwarf models with $T_{eff} = 22{,}000K \pm 1000K$, log g = 7.5 ± 0.3, V sin *i* $\simeq$600 km/s are shown. Both models (22 and 23) have the following chemical abundances: Fe = 0.1 times solar, S = 0.5 times solar; all other heavy elements are 0.15 times solar except Al. In model 22, Al = 15 times solar, while in model 23, Al = 5 times solar.

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