Optical Spectroscopy of V4334 Sgr: 1996-2000

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The evolution of V4334 Sgr, or Sakurai's object, from its discovery as an early F supergiant in 1996 to its fading as a late K-type supergiant during 1999 was, in terms of normal stellar behaviour, unprecedented. That evolution was primarily manifest through gross photometric changes (Nakano et al., 1996). It was quickly suggested that V4334 Sgr is a rare example of a hot evolved low-mass star, possibly a white dwarf, in which nuclear reactions in the helium shell have been reignited, causing the star to expand to giant dimensions (Benetti et al., 1996b).

From discovery onwards, substantial changes in the optical spectrum have been apparent. This paper reviews these changes, drawing on published and unpublished material. It sets out the measurements necessary for understanding the evolution of the star, and attempts to assess the quantitative deductions made from the spectroscopic observations.

In the course of other observational work, both authors have acquired a number of spectra of V4334 Sgr. This review presents a number of these for the first time, including a unique record of the spectral evolution around Hα during 1996. We have begun independent analyses of these spectra and of an échelle spectrum obtained im 1996 May. Some preliminary results are included.

Prior to writing this paper, the principal author had not been involved in any completed analysis of V4334 Sgr and he has attempted to be impartial in reviewing the literature. However his own experience of modelling stellar atmospheres of peculiar composition and of studying the spectra presented here have no doubt affected his judgement. He takes full responsibility for the selection of material to include and regrets any major omissions.

1. What we want to know and why.

In order to understand the evolution of V4334 Sgr, detailed information concerning the stellar surface properties throughout the period of visibility is of fundamental importance. Most of this information is provided by the optical spectrum. The following are of interest.

Spectral Classification. A spectral type provides a model-independent description of fundamental stellar properties and enables comparative analyses to be carried out objectively and economically. For these reasons, descriptions of the spectral evolution of V4334 Sgr from even modest resolution spectrographs can be enormously helpful for tracing the evolution, particularly during intervals when high-resolution data are not available.

Photospheric Diagnostics. Where the data is of sufficient quality, optical spectra provide measurements of effective temperature ($T_{\rm eff}$), chemical composition and surface gravity (log g), the latter with $T_{\rm eff}$ being a proxy for the luminosity to mass ratio (L/M).

Circumstellar Diagnostics. The optical spectrum also carries information concerning material above the stellar photosphere, including gas in a stellar wind accelerating away from the stellar surface, dust which may have condensed from the ejected gas several stellar radii from the surface, and ionized material in a planetary nebula ejected by the star in an earlier epoch of evolution. This review deals only with the photospheric diagnostics.

The measurements outlined above may be used to address the following questions: What track has V4334 Sgr followed through the Hertzsprung-Russell diagram? How has its surface composition changed during that evolution? Is V4334 Sgr similar to any other stars? What are the evolutionary origin and fate of V4334 Sgr?

2. Optical Spectroscopy.

2.1. A POSSIBLE FINAL HELIUM FLASH.

The outburst of V4334 Sgr was discovered on 1996 Feb 20 (Nakano et al., 1996). The first published low-resolution spectrum was obtained on 1996 March 8.4 by Duerbeck & Benetti (1996), who found that it most closely resembled that of an early-F supergiant. However the Balmer lines were appreciably weaker than in normal F supergiants, whilst carbon and oxygen appeared to be overabundant. This description corresponds precisely with the spectral characteristics of some R Coronae Borealis (RCrB) stars, although the Balmer lines in V4334 Sgr may have been stronger than in *most* of the latter. Prompted by the speculation that V4334 Sgr is an example of a “fast final helium flash object” (Benetti et al., 1996b, Duerbeck & Pollacco, 1996), the rapid evolution of V4334 Sgr was compared to that of FG Sge (van Genderen &

Gautschy, 1995) and V605 Aql (Seitter, 1987) and with the predictions of early theoretical models (Iben et al., 1983, Iben, 1984).

2.2. THE ONCE AND FUTURE FAINT BLUE STAR.

The first quantitative analysis of the surface characteristics of V4334 Sgr was presented by Shetrone & Keane (1997) and based on a high resolution ($R = 14\,000$) spectrum obtained on 1996 April 20, exactly two months after discovery. Qualitatively, this spectrum also exhibits many features found in RCrB stars but continues to show much stronger hydrogen lines. The abundance analysis was carried out using an LTE spectral synthesis code and Kurucz model atmospheres, leading to a derivation of the following characteristics: $T_{\rm eff} = 7\,750 \pm 250\,{\rm K}$, $\log g = 1.0 \pm 0.5$, $[{\rm Fe/H}] = 0.10 \pm 0.22$. The hydrogen abundance was estimated to be $< 20\%$ depleted. The authors were cautious about their results, doubting the legitimacy of the adopted model atmospheres. They concluded that, while V4334Sgr might possibly join V854 Cen as a hydrogen-rich RCrB star (Rao & Lambert, 1996), there were important differences to typical RCrB abundances. However, the authors took the view that the measurements were acceptably consistent with the evolution of a final helium flash object – a faint blue star that evolves rapidly to become a red giant and will one day contract to become a faint blue star once more.

2.3. A STELLAR ENDGAME.

This view was also reflected in a paper by Asplund et al. (1997) in which high-resolution optical spectra ($R \sim 30\,000$) obtained on 1996 May 5,6 and October 7 were found to show a 0.7 dex decrease in surface hydrogen abundance and 600 K decrease in $T_{\rm eff}$ over a five month interval. These changes were accompanied by an increase of Li and s-process elements Sr, Y and Zr. Asplund et al. (1997) used hydrogen-deficient model atmospheres in their analysis. Their conclusion that V4334Sgr was 2.3 dex underabundant in H in 1996 May contrasts starkly with the preliminary result of Shetrone & Keane (1997) ($\sim$ 0.1 dex). An increase of 0.5 dex in $\log g$ in the same five months, corresponding to a decrease in L by a factor 4 is not consistent with the photometry (or stellar physics), prompting a suggestion of significant departures from hydrostatic equilibrium on one (or both) dates of observation.

2.4. THE CHEMICAL COMPOSITION.

A consequence of the excitement generated by the outburst of V4334 Sgr was the collection of high-resolution spectra by a large number of observers (the curent authors being no exception). Kipper & Klochkova (1997) report the analysis of a spectrum obtained on 1996 July 3 with $R \sim 20\,000$. Their qualitiative description again gives a spectral type of F2-3II, resembling the majority of R CrB stars but with stronger Hα than most of the latter. A quantitative analysis using hydrogen-deficient model atmospheres found a 2.4 dex underabundance in H, with other species broadly similar in abundance to those found by Asplund et al. (1997).

2.5. THE RAPID EVOLUTION: A RETROSPECTIVE.

Following these early publications, a more measured analysis of the spectral evolution during 1996 and beyond was presented by Asplund et al. (1999). High-resolution spectra obtained at five epochs (1996 April 20–25, May 5–9, June 4, July 3, and October 7) were analysed in a consistent manner, demonstrating the evolution of V4334 Sgr in $T_{\rm eff}$ and L. Asplund et al. (1999) adopted the same assumptions of plane-parallel geometry, local thermodynamic and hydrostatic equilibrium and appropriately hydrogen-deficient model atmospheres as Asplund et al. (1997).

Both the spectroscopic and photometric records (Duerbeck et al., 1997) showed a linear decrease in $T_{\rm eff}$ from $7\,750 \pm 300$ K on 1996 April 20 to $6\,900 \pm 300$ K on October 7. Duerbeck et al. (1997) showed this trend to continue into 1997.

Leaving aside, briefly, the question of chemical evolution, a crucial question concerns the luminosity of V4334 Sgr over the same interval. The principal spectroscopic proxy for L is surface gravity; Asplund et al. (1999) found values from $\log g = 0.25 \pm 0.3$ in April, via 0.00 ± 0.3 in May, to 0.50 ± 0.30 in October. Considering the formal errors alone, the apparently large variation is consistent either with evolution at constant luminosity or a linear reduction in luminosity by a factor four over the six month interval. The apparent contradiction with Duerbeck et al. (1997) who report a luminosity increase of 30% over the same interval might be resolved by introducing bolometric corrections appropriate to the peculiar composition of this star.

As noted already (Asplund et al., 1997), the major problem admitted in this and all previous analyses is the assumption of hydrostatic equilibrium. Both Asplund et al. (1999) and Duerbeck et al. (1997) arrive at the same conclusion. Evidence includes a decrease in microturbulent velocity ($v_{\rm t}$) from near $10.5\,{\rm km\,s^{-1}}$ in April to $6.5\,{\rm km\,s^{-1}}$ in October.

From April to May at least, the luminosity is close to or exceeds the classical Eddington limit. A trivial calculation is instructive. With $M \sim 0.8\,\mathrm{M}_\odot$, $\log g \sim 0.3$, the stellar radius is $\sim 100\,\mathrm{R}_\odot$. If the star reached this radius in 200 days or less at a *uniform* expansion rate, the surface expansion velocity would be $\sim 2\,\mathrm{km\,s}^{-1}$ which approaches the sound-speed in the atmosphere of an F supergiant. Consequently, the interpretation of the earliest spectra, at least, and possibly of all the spectra, should be treated with circumspection. However, in the absence of suitable models for expanding atmospheres and, in particular, any diagnostics with which to reconstruct the structure of the expanding envelope, the use of plane-parallel LTE models in hydrostatic equilibrium remains the most powerful tool available.

The most remarkable result arising from the work by Asplund et al. (1997) and Asplund et al. (1999) is the dramatic change in surface composition. While the abundances of most elements (He, C, N, O, Ne, Mg, Al, Si, P, S, K, Ca, Fe, Ni and Cu) remained the same throughout 1996, there were significant changes in H (decrease by 1.0 dex), Li (increase by 0.6 dex), Sc, Zn, Rb and Y (+0.7 to +1.0 dex) and probably Ti, Cr, Sr and Zr (+0.5 to +0.7 dex). There are good reasons for supposing the abundance changes to be real, not least the absence of changes in the majority of elements.

Although constant, the relative surface abundances of non-varying elements is far from solar. Large overabundances of He, C (1.2 dex), N (1.1 dex), O (0.5 dex) and Ne (1.4 dex) point to a surface which has been heavily processed through hydrogen and helium-burning stages. Overabundances of Li and s-process elements provide further evidence of past episodes of nucleosynthesis. Asplund et al. (1999) discuss these at length; apparent corollaries are found in FG Sge (Gonzales et al., 1998) and R CrB stars (Asplund et al., 2000). The overall metallicity (relative to solar) is harder to assess because of the carbon problem. With background opacities defined by C/He=10%, the mean metallicity is only 0.2 dex below solar, but with C/He=1%, it becomes 0.9 dex below solar.

The evolution framework considers a post-AGB star in which the outer layers are already enriched in several species, including C,N and O, and s-process elements, although not all are manifest at the stellar photosphere. During and after a final helium-shell flash, H-rich material (protons) and heavy elements are mixed at high temperatures, possibly spawning a new episode of nucleosynthesis. As the star expands and cools, convection in the surface layers dredges both AGB and final-flash products to the stellar surface. Asplund et al. (1999) propose that this is the process responsible for the changing surface abundances of V4334 Sgr observed in 1996.

If the onset of convection is responsible for the abundance changes, the proposed framework raises both questions and problems. One question concerns how much dredged-up material was produced in the final shell flash and how much during preceding shell flashes on the AGB. A problem concerns the efficiency of convective dredge-up; Blöcker (2000) shows that for a theoretical post-AGB star undergoing a late thermal pulse (a final flash when the star is on the constant luminosity segment of the post-AGB track), dredge-up only starts after the star reaches minimum effective temperature ($\sim 6\,700$ K). A very late thermal pulse (FF on the white dwarf cooling track) produces stars that are already H-deficient before they reach maximum radius (Herwig et al., 1999). The ramifications of these evolution models are discussed elsewhere (Herwig, 2000), but neither fits the observations of V4334 Sgr particularly well.

2.6. THE DEVELOPMENT OF THE MOLECULAR ABSORPTION SPECTRUM.

By October 1996, the Swan bands of C_2 had become detectable as $T_{\rm eff}$ dropped below 7 000 kelvin, and proceeded to strengthen through 1997 and 1998. Asplund et al. (1999) showed how line crowding increased dramatically over the same period. making continuum placement and the measurement of accurate abundances increasingly difficult. Strong CN bands (red and violet) were also seen to develop. Pavlenko et al. (2000) succeeded in modelling the increasingly complex molecular spectrum from a grid of hydrogen-deficient and carbon-rich model atmospheres, and deduced $T_{\rm eff} \approx 5\,500$ K in 1997, April. This is $\sim$ 500 K lower than indicated by Duerbeck et al. (1997) from photometry, and below the linear trend indicated througout 1996. Although the spectroscopic measurement may be realistic, the model atmosphere calculations are still in their infancy.

A comparison with the FAST stellar spectral atlas (URL: http://cfa-www.harvard.edu/~pberlind/atlas/atframes.html) shows the 1997 April spectrum of V4334 Sgr to approximately resemble the carbon star HD-182040, with spectral type C-R2. With $T_{\rm eff} \sim 4\,500$ K, this assignment may be too late for V4334 Sgr; a more precise classification is required.

In early 1998, V4334 Sgr started to show a large-amplitude decrease in brightness (Duerbeck et al., 2000) likened, initially, to an RCrB-type fading event (Liller et al., 1998a, Liller et al., 1998b). The formation of obscuring dust was evident from an increasing infrared excess, but, unlike RCrBs, the optical extinction continued to increase, exceeding 11 magnitudes by mid 1999 (Duerbeck et al., 2000) and from which it

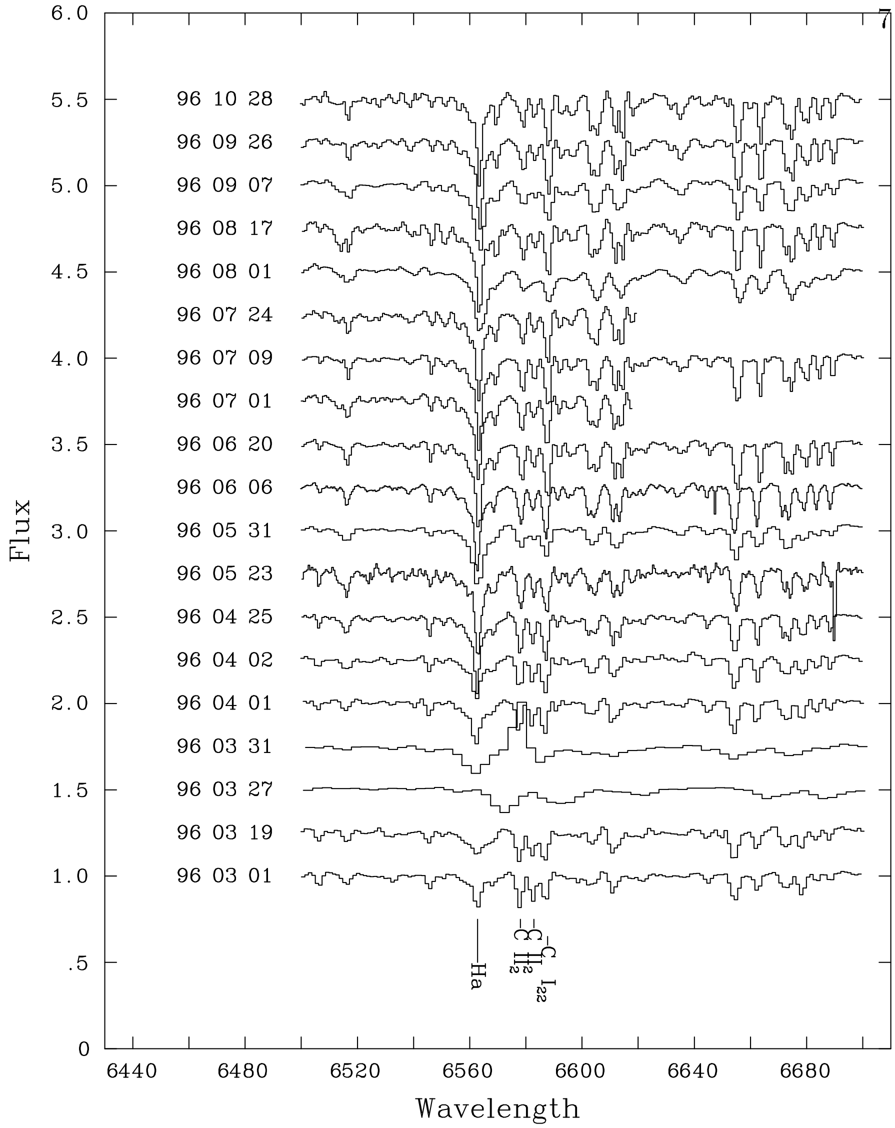


Figure 1. Evolution of the optical spectrum of V4334 Sgr during 1996. The date of each observation is shown on the left (yy mm dd); all spectra are shown normalized and offset. Selected aborption lines are identified.

has not recovered. Under these circumstances, high-resolution optical spectroscopy has all but ceased.

3. The Isaac Newton Telescope Record.

Following the discovery of V4334 Sgr on 1996 February 20, one of us (DLP) began to obtain optical spectroscopy from the La Palma Ob-

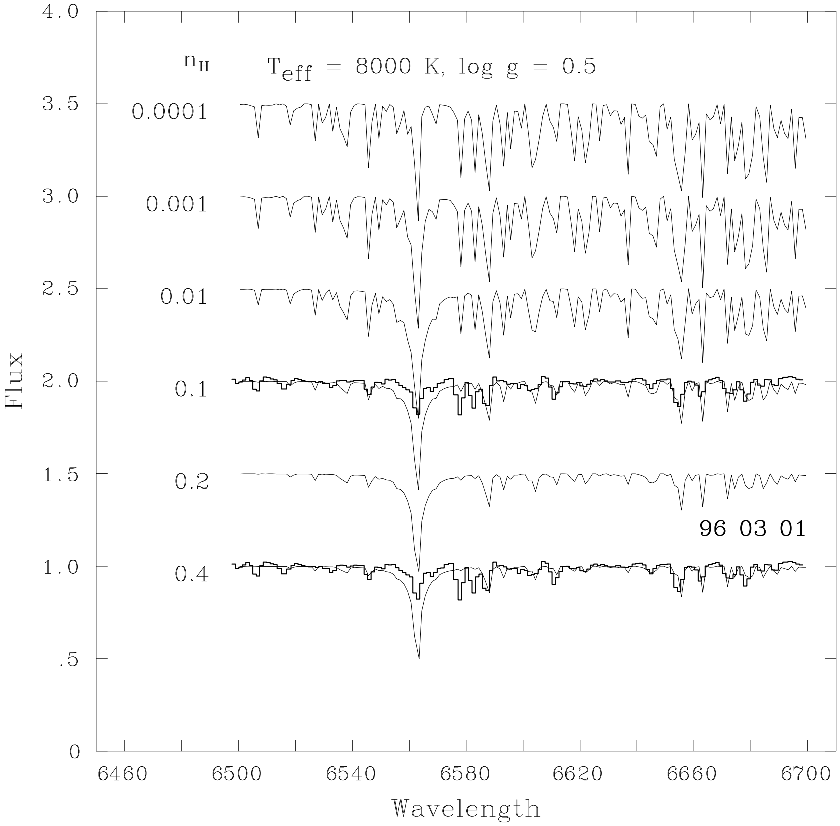


Figure 2. Model spectra with varying hydrogen abundance ($n_{\rm H}$) and $T_{\rm eff} = 8000$ K, compared with the spectrum of V4334 Sgr on 1996 March 1 (heavy line). The carbon abundance is $n_{\rm C} = 0.01$.

servatory, mostly with the intermediate dispersion spectrograph on the Isaac Newton Telescope but also partly with ISIS on the William Herschel Telescope. Various resolutions up to $\sim 5\,000$ were used, mostly in the optical red. The record begins on 1996 March 1 (the first spectrum to be obtained following discovery) and continues with a frequency of at least one observation per month (Sun permitting) up to the deep decline of 1999.

The spectral evolution around Hα from 1996 March to 1996 October is illustrated in Fig. 1. Note in particular the changing ratio of the C II and C I line strengths.

Preliminary attempts have been made to simulate the evolution of the spectrum, with limited success. Model atmospheres with R CrB mixtures (C/He=1%) computed for analysis of R CrB stars (Asplund et al., 2000) were kindly made available by Martin Asplund. These were used as input to Kurucz' spectral synthesis code SYNTHE in the

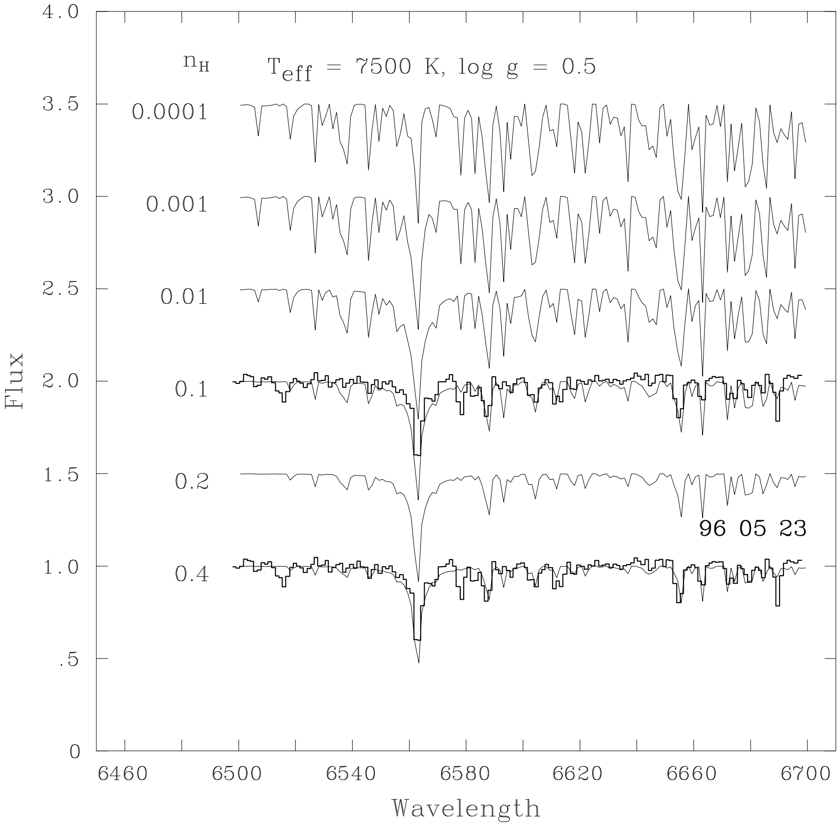


Figure 3. As Fig. 2 but with $T_{\text{eff}} = 7500\,\text{K}$ and the spectrum of 1996 May 23.

implementation described by Jeffery et al. (1997). A grid of high-resolution model spectra was generated with $T_{\text{eff}} = 5\,000 - 8\,000\,\text{K}$, $\log g = 0.0 - 1.5$ (cgs) and $n_{\text{H}} = 0.0001 - 0.4$. These were binned to match the resolution of the INT spectra (Figs. 2 to 4).

The model spectra do not yet account correctly for the C II lines, so the carbon abundance will need to be examined. Significant changes will be necesssary in order to reconcile the 1996 October spectrum with the hydrogen abundance ($n_{\text{H}} = 0.004$) reported by Asplund et al. (1999). In our models, such a low abundance leads to a line spectrum very much stronger than observed. We expect that increasing the C abundance and, hence, the background opacity in the input models will resolve this problem.

The behaviour of Hα is interesting. In our 1996 March 1 spectrum, it is too weak compared with any theoretical models. It remains weak through March (spectra from March 27 and 31 are not sufficiently resolved), beginning to strengthen around April 1. The central intensity

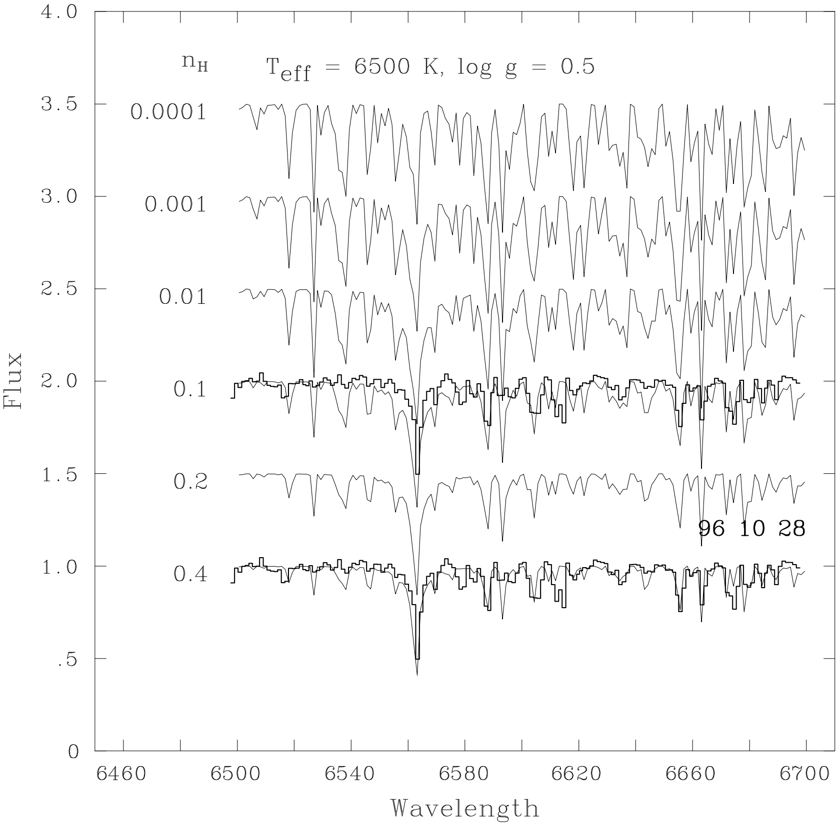


Figure 4. As Fig. 2 but with $T_{\rm eff} = 6500$ K and the spectrum of 1996 Oct 28.

approaches that of the LTE hydrostatic models by July. It is clear that this line cannot be simulated with equilibrium models during the first few months of evolution, as already concluded by Asplund et al. (1999).

4. Echelle spectroscopy

A high-resolution spectrum was obtained (by CSJ) with the UCL échelle spectrograph at the Anglo-Australian Telescope on 1996 May 15 with wavelength coverage 3800 - 5050 Å. In parallel with our analysis of the INT record, we have begun an analysis of this spectrum using an independent set of hydrogen-deficient model atmospheres. Complete details of the model atmosphere and spectrum synthesis codes may be found elsewhere (e.g. Jeffery & Heber, 1992, Jeffery et al., 2001). For this investigation, new model atmospheres have been computed on the grid $T_{\rm eff} = 6\,000(500)8\,000(1\,000)10\,000$ K, $\log g = 0.0(0.5)1.0$, $n_{\rm H} = 0.01, 0.05$, $n_{\rm C} = 0.005, 0.03, 0.10$.

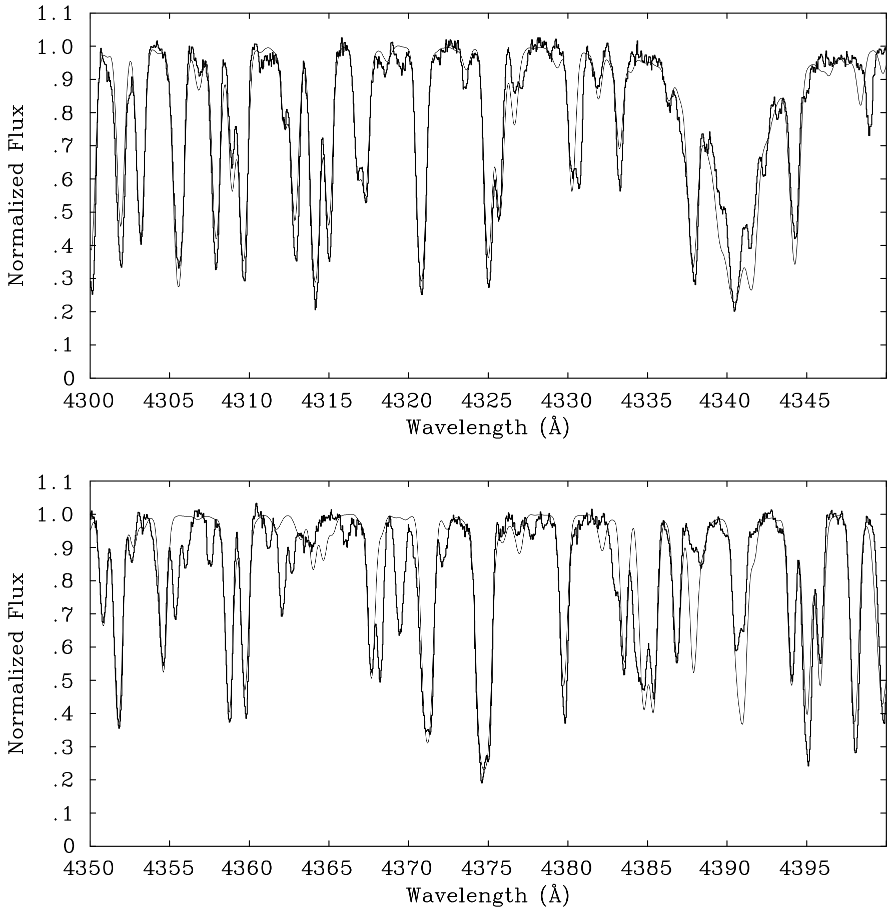


Figure 5. AAT échelle spectrum of V4334 Sgr (bold histogram) obtained on 1996 May 15, together with best-fit synthetic spectrum (smooth curve) in the region of Hγ.

The region of the spectrum around Hγ is shown in Fig. 5, together with the best fit synthetic spectrum so far obtained from an iterative χ^2-minimization procedure. Because of the large number of degrees of freedom, the procedure is fragile and improvements will no doubt be made. Significant problems currently include incompleteness and inaccuracies in the atomic linelists, where we have considered approximately 2 500 lines in the interval 4 200-4 500 Å.

To derive the basic parameters $T_{\rm eff}$, $\log g$, $n_{\rm H}$, $n_{\rm C}$, and $v_{\rm t}$, a 5-dimensional grid of synthetic spectra was computed from the model atmosphere grid. Best-fit solutions were obtained within this grid for up to five simultaneous independent parameters, including the rotational broadening $v \sin i$. Thus the hydrogen abundance was deduced from

Table I. Provisional atmospheric parameters for V4334 Sgr derived from an AAT échelle spectrum obtained on 1996 May 15. Abundances are given as $\log n + c$, normalized such that $\sum \log \mu n = 12.15$. These preliminary values are compared with May 5–9 results for V4334 Sgr (Asplund et al., 1999) and the Sun (Grevesse & Sauval, 1998). Values marked ':' are uncertain. Velocities are in $\mathrm{km\,s^{-1}}$.

	1996	1996	Sun		1996	1996	Sun
	May 15	May 5–9			May 15	May 5–9	
$T_{\rm eff}$ / K	8300	7500		H/He	0.07		
log g	0.50	0.00		C/He	0.05	0.10	
$v_{\rm t}$	7.50	8.0		v sin i	17		
H	10.3	9.7	12.00	Sc	3.7	3.1	3.17
He	11.2	11.4	10.93	Ti	4.3	4.1	5.02
C	10.3	9.7	8.52	V	3.1		4.00
N	7.9	8.9	7.92	Cr	4.3	4.5	5.67
O	7.9:	9.5	8.83	Mn	4.8		5.39
Mg	7.2	6.6	7.58	Fe	6.6	6.4	7.50
Al	6.4	6.6	6.47	Ni	6.5	6.1	6.25
Si	7.3	7.1	7.55	Sr	4.9	4.9:	2.97
P	5.4:	6.2	5.45	Y	3.2	3.3	2.24
S	7.1	6.6	7.33	Zr	2.1	3.0	2.60
				Ce	1.0		1.58

models with carbon abundances $n_{\rm C} = 0.005, 0.03$ and 0.10, giving $n_{\rm H} = 0.07 \pm 0.01$. The carbon abundance was then deduced from the best fit in a grid with $n_{\rm H}$ fixed. Note that this takes into account the overall effect of carbon on the absorption spectrum, including its contribution to the continuous opacity.

Having established the basic parameters, a new model atmosphere was computed and used as input to a second χ^2-minimization procedure. This computes synthetic spectra in which one or more elemental abundances and $v_{\rm t}$ are free parameters.

As with all quantitative analyses of spectra in which the dominant opacity source is not well defined, the overall procedure from model atmosphere to derived abundances is intensively iterative. The results presented here (Table I) require further iteration in order to ensure the correct composition of the input model atmospheres. They are currently based on only 300 out of a possible 1200Å of spectrum. The results are therefore presented as provisional and without error estimates.

There are significant differences to the analysis of spectra obtained 6 to 10 days previously and reported by Asplund et al. (1999). The most obvious are in $T_{\rm eff}$ and $\log g$; these can probably be accounted for by differences in the opacities used in constructing the model atmospheres. Our analysis gives higher abundances for both hydrogen and carbon by a factor four which may be significant. In general the results for other abundances are similar for both the May 5–9 and May 15 spectra, despite the difference in analysis methods. However we find that compared with Asplund et al. (1999) i) V4334 Sgr is not so nitrogen rich, ii) other light elements (Mg, Al, Si, P, S) follow the solar values more closely, iii) V4334 Sgr may be richer in iron-group elements (Sc – Ni) and iv) light s-process elements Sr and Y are confirmed to be overabundant, but not Zr. Since the data, models, and methods are all completely independent it will eventually be instructive to study the systematics of these differences in greater detail.

5. Future model atmosphere requirements for V4334 Sgr

The object of constructing model atmospheres for V4334 Sgr is to be able to deduce the physical properties of the star from the observed spectrum. As described elsewhere in these proceedings, existing models have already succeeded in describing many of the gross properties of V4334 Sgr during 1996. Consequently we know that model atmospheres must be valid for a parameter space defined by effective temperature: $T_{\rm eff} \sim 5\,000 - 9\,000$ K, surface gravity: $\log g \lesssim 1$ (cgs), hydrogen abundance: $n_{\rm H} \lesssim 10\%$ (by number) and carbon abundance: $n_{\rm C} \gtrsim 1 - 10\%$ (by number).

Thus it is clear already that models must be able to treat very low surface gravities and unusual compositions. To a good approximation, these are all problems which have been dealt with using classical assumptions of plane-parallel geometry, local thermodynamic, hydrostatic and radiative equilibrium, and contemporary methods for the calculation of continuous and line opacities.

As a contribution to the closing discussion, the principal author was asked to suggest directions future model atmospheres calculations might take. There are three drivers for this. One is to introduce greater physical realism, the second is to solve problems that cannot be treated under classical approximations and the third is to make predictive models to facilitate tests of stellar evolution theories.

The major problems encountered during existing analyses of the spectral evolution through 1996 concern the treatment of opacities. The carbon problem is extensively discussed by Asplund et al. (1999), but there are signs that it may now be reaching a resolution (Kipper, private communication). The combination of low effective temperature and very low surface gravity together with an unusually carbon-rich chemistry and forests of molecular lines creates a substantial demand for molecular data and new methods to include these in spectral synthesis calculations. Pavlenko et al. (2000) are making progress in this area. However there remain important issues to address.

5.1. NON-LOCAL THERMODYNAMIC EQUILIBRIUM

As is common in supergiant atmospheres, the combination of very low density and high luminosity means that atomic and molecular level populations may not be fully thermalized. Some effort should be made to measure the extent to which departures from LTE are important.

5.2. SPHERICAL GEOMETRY

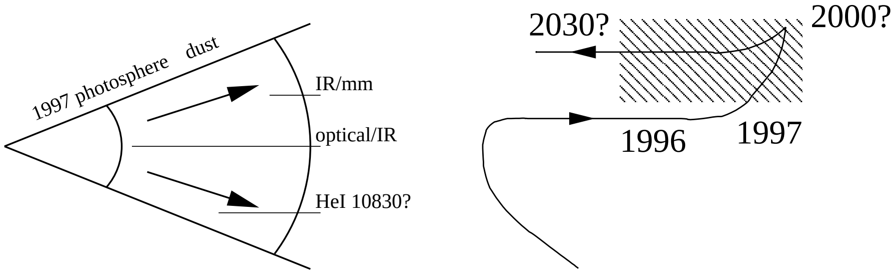
A cursory inspection of the geometrical extent of a plane-parallel LTE model atmosphere for a normal F-supergiant ($T_{\rm eff}$=8 000 K, log g=0.5, $n_{\rm H}$=0.90) is instructive. Between optical depths $\tau = 10^{-3}, 10^{-1}$ and unity lie distances of 59 and 34 $R_{\odot}$ respectively. A low-opacity hydrogen-deficient atmosphere is even more extended. These depths are to be compared with a stellar radius ($M = 0.8\,{\rm M}_{\odot}$) of $\sim 100\,{\rm R}_{\odot}$. Under such circumstances, the plane-parallel approximation may be untenable.

5.3. EXPANSION, ROTATION, AND TURBULENCE

During 1996, V4334 Sgr expanded from white dwarf dimensions to $\sim 100\,{\rm R}_{\odot}$ in approximately one year. If the surface had been propelled outward at uniform velocity, this would correspond to a surface expansion velocity $\sim 2\,{\rm km\,s}^{-1}$. The outer atmosphere would be expanding at least twice this rate. To first order, the differential expansion of the atmosphere represents a negligible departure from hydrostatic equilibrium. For example, there is no evidence of expansion-induced line asymmetry in the optical échelle spectrogram from May 1996.

If the outer layers of a rotating star are rapidly propelled to larger radii, conservation of angular momentum demands that their rotation velocities decrease as a function of radius, and hence, in the case of V4334 Sgr, of time. Given its extent, differential rotation will also affect the radiative layers of the atmosphere. However, by the time V4334 Sgr was discovered, its rotation velocity was already small (we found $v \sin i \sim 17\,{\rm km\,s}^{-1}$) so the effects of rotational deceleration and differential rotation on the spectrum will be modest.

The sound speed in the atmospheres of F supergiants is $\lesssim 5\,{\rm km\,s}^{-1}$. The boundary between the expanding atmosphere and the local interstellar medium may thus constitute a mild shock front. The supersonic



a. Extended atmosphere in 2000 b. Evolution through HR diagram

Figure 6. Schematic representations of (a) the extended envelope of V4334 Sgr, illustrating where different observed features may originate, and and (b) its visible evolution to low effective temperature, its possible current location obscured by dust and its possible future evolution.

microturbulent velocity $v_{\rm t} \sim 8\,{\rm km\,s^{-1}}$ (Asplund et al., 1999) also points to a turbulent atmosphere, possibly disrupted by local instabilities or shocks. Other evidence of disruption is provided by evidence for Hα emission discussed above.

5.4. DUST

During and after 1997, the formation of dust poses a whole new series of problems for modelling the atmosphere which now consists of several components. The classical photosphere, where the previously visible optical spectrum would have been formed and now with $T_{\rm eff} \sim 5-7\,000\,{\rm K}$, can no longer be seen (Fig. 6a). In its place, an infrared continuum formed by condensed dust at much lower temperatures is seen. Superimposed on this IR continuum is an emission line due to He I 10830 Å. What is the extent of coupling between the original photosphere and the newly formed dust cloud? Where is the He I line formed and what does it tell us about the physics of the extended atmosphere? New models will have to deal with all of these problems.

6. The future evolution of V4334 Sgr

Both stellar evolution theory and historical precedent suggest that V4334 Sgr will eventually start to contract and once again become first a hot planetary nebula central star and then a white dwarf. As it heats, ultraviolet radiation will dissociate, disperse and ionize the dust cloud now surrounding the star, so that clumps of hydrogen-deficient gas and dust may be seen within the existing planetary nebula. How long it will be before that occurs is contentious; theoretical models suggest that contraction times for final-flash stars are ~ 10 times the expansion times (Blöcker & Schönberner, 1997), so it may be 10–30 years before V4334 Sgr reappears from behind its obscuring cocoon (Fig. 6b).

In the meantime, the only data which tells us about the chemical evolution of the stellar surface as V4334 Sgr approached maximum radius is contained in those optical spectra obtained between 1996 February and 1998 April. It is essential that this brief record be preserved, and every effort made to apply the best theoretical models to ascertain how the stellar surface responded to the flash event.

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