The Hubble-Sandage Variable HDE 269006: A Hot Supergiant with a Cool Envelope

I. Appenzeller, O. Stahl and B. Wolf, Landessternwarte Heidelberg

I. Motivation and Observations

The class of bright blue variable stars, which we call "Hubble-Sandage" or "S Dor" variables, contains some of the most luminous stars known in the universe. At maximum light at least their visual brightness may surpass that of any known non-variable star. Because of their high luminosity and since these stars can be distinguished from faint galactic foreground stars by their particular light curves, the identification of such objects in extragalactic systems is relatively easy, and a considerable number of these stars has been discovered in nearby galaxies. Since they can be detected over so large distances, Hubble-Sandage variables could in principle provide a useful tool in the calibration of the extragalactic distance scale and in studies of the physical conditions in extragalactic systems. However, before such investigations can be considered, we first have to learn much more about the nature and structure of these stars. Since all these objects are blue and since as a rule Hubble-Sandage variables are surrounded by dense expanding circumstellar envelopes, spectroscopic observations at ultraviolet wavelengths (where the most common ions in these envelopes have their strongest spectral lines) are particularly important for clarifying the nature of these stars. Therefore, we used the International Ultraviolet Explorer (IUE) satellite to observe some of these objects. In addition we used the ESO observatory at La Silla to supplement the satellite observations with ground-based spectroscopic data obtained at the same epoch as the IUE observations. As described in detail below, it was just this possibility of doing (almost) simultaneous observations from space and from the ground that made firm conclusions on at least some aspects of these stars possible.

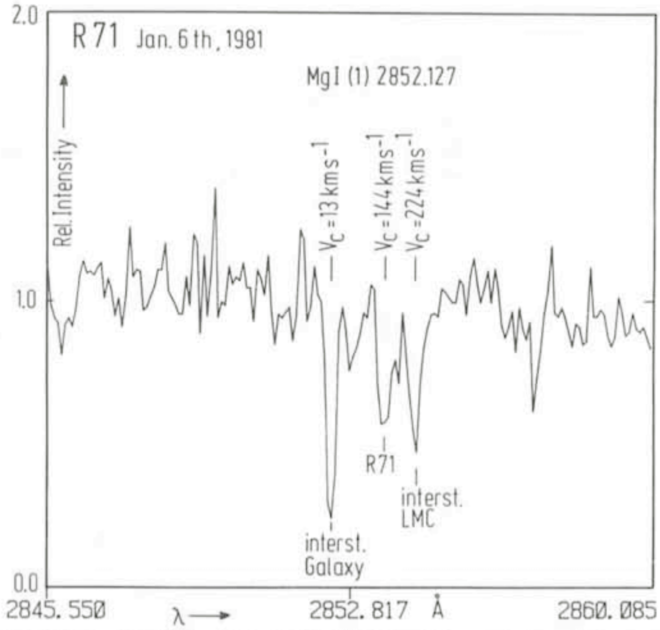

Fig. 2: *The Mg I (1) resonance line in the minimum state spectrum of HDE 269006 = R 71. Because of the high photospheric temperature, there is practically no photospheric contribution to this feature. The absorption component at v = 144 km s^{-1} is produced by the expanding circumstellar envelope, while the other two components are due to interstellar gas in our Milky Way galaxy and in the LMC. Note the different strength of the two interstellar components.*

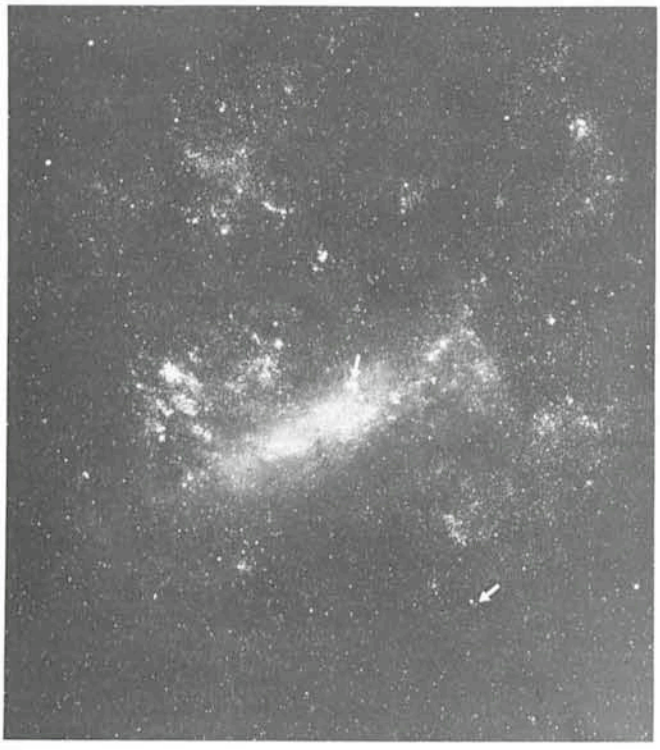

Fig. 1: *The location of the two known Hubble-Sandage variables in the Large Magellanic Cloud. S Dor is in the bright nebulosity near the centre of the image, HDE 269006 is in the lower right-hand (= SW) part. Both stars are indicated by arrows. (Photograph by R. Knigge, 10 inch Metcalf Refractor, Boyden Observatory).*

Although several S Dor-like variables are known in our Milky Way galaxy (notably the peculiar object η Car), light extinction by interstellar dust in the galactic plane (which is particularly strong in the UV) makes UV spectroscopy of these galactic objects difficult. Fortunately, in our neighbouring Large Magellanic Cloud (LMC) galaxy two relatively bright Hubble-Sandage variables are known, which are less affected by interstellar dust extinction. One of these two is the star S Dor which is located close to the centre of the LMC. S Dor was the first Hubble-Sandage variable to be discovered (in 1897 by Pickering), and it is for this reason that many authors prefer to call this class of variable stars the "S Doradus variables". S Dor also was the first star of this type to be investigated by us with the IUE satellite. However, since our results on S Dor have already been published (cf. Wolf, Appenzeller, and Cassatella 1980, *Astronomy and Astrophysics*, **88**, 15) they will not be included in this short report. The second known Hubble-Sandage variable in the LMC is the star HDE 269006 or "R 71". (The latter and shorter designation is its number in the Radcliffe catalogue of bright LMC stars.) R 71 was identified as an S Dor-type variable by Thackeray in 1974. In contrast to S Dor, R 71 is located at a considerable distance from the centre of the LMC (cf. Figure 1), but its radial velocity definitely proves that R 71 is a member of the LMC. As noted already by Thackeray, the properties of S Dor and R 71 (including their spectra) are strikingly similar (if observed at the same lightcurve phase!), except for the fact that R 71 has a hotter photosphere. Like other Hubble-Sandage variables R 71 shows a lightcurve which (although being clearly not strictly periodic) consists of extended maximum and minimum phases, lasting typically about a decade, separated by relatively short transition periods. The last maximum phase of R 71 occurred between about 1970 and 1977, when the star had a visual magnitude of about $m_v = 9.9$. Since sometime in 1978 (when the IUE satellite was launched) R 71 is again in its minimum state, fluctuating slightly around $m_v = 10.9$. Although this is rather faint for high-resolution spectroscopy with the IUE satellite (which after all has only a 45 cm telescope) we knew that the star is relatively hot (photospheric spectral type during the minimum state: B 2.5 Iep) and we therefore expected such observations to be just possible. Indeed, two very long IUE exposures, each lasting more than seven hours, obtained in January 1981, resulted in two well-exposed high-resolution spectrograms, which together cover the wavelength range 1250 to 3200 Å. Coudé spectrograms obtained at the ESO 1.5 m telescope at the same epoch cover the wavelength range 3550 to 4900 Å. For technical reasons it was not possible to take simultaneously spectrograms in the red spectral range. However, for completeness, one week earlier we had obtained several low-resolution image-tube spectrograms of R 71 covering the wavelength range 5400 to 7000 Å. These plates showed that at least the basic properties of the red spectrum had remained unchanged since our high-resolution spectroscopic observations of the H_α region carried out 14 months earlier at the beginning of the present minimum of R 71. The spectroscopic observations were supplemented by photometric observations which Dr. S. Wramdemark kindly carried out for us at ESO.

II. Results

There are two main results of our coordinated IUE and ground-based observations of R 71: Firstly, our observations allowed to derive the continuum energy distribution of R 71 for all wavelengths which contribute significantly to the total luminosity of this star. From an integration of the energy distribution and from the known distance of the LMC we were able to calculate the (minimum state) total luminosity of R 71 which was found to be about 200,000 times the solar luminosity. In addition, the shape of the energy distribution allowed us to estimate the photospheric effective temperature (about

Tentative Time-table of Council Sessions and Committee Meetings

November 10	Scientific Technical Committee
November 11 – 12	Finance Committee
November 13	Committee of Council
Nov. 30 – Dec. 1 – 2	Observing Programmes Committee
December 3 – 4	Council

All meetings will take place at ESO in Garching.

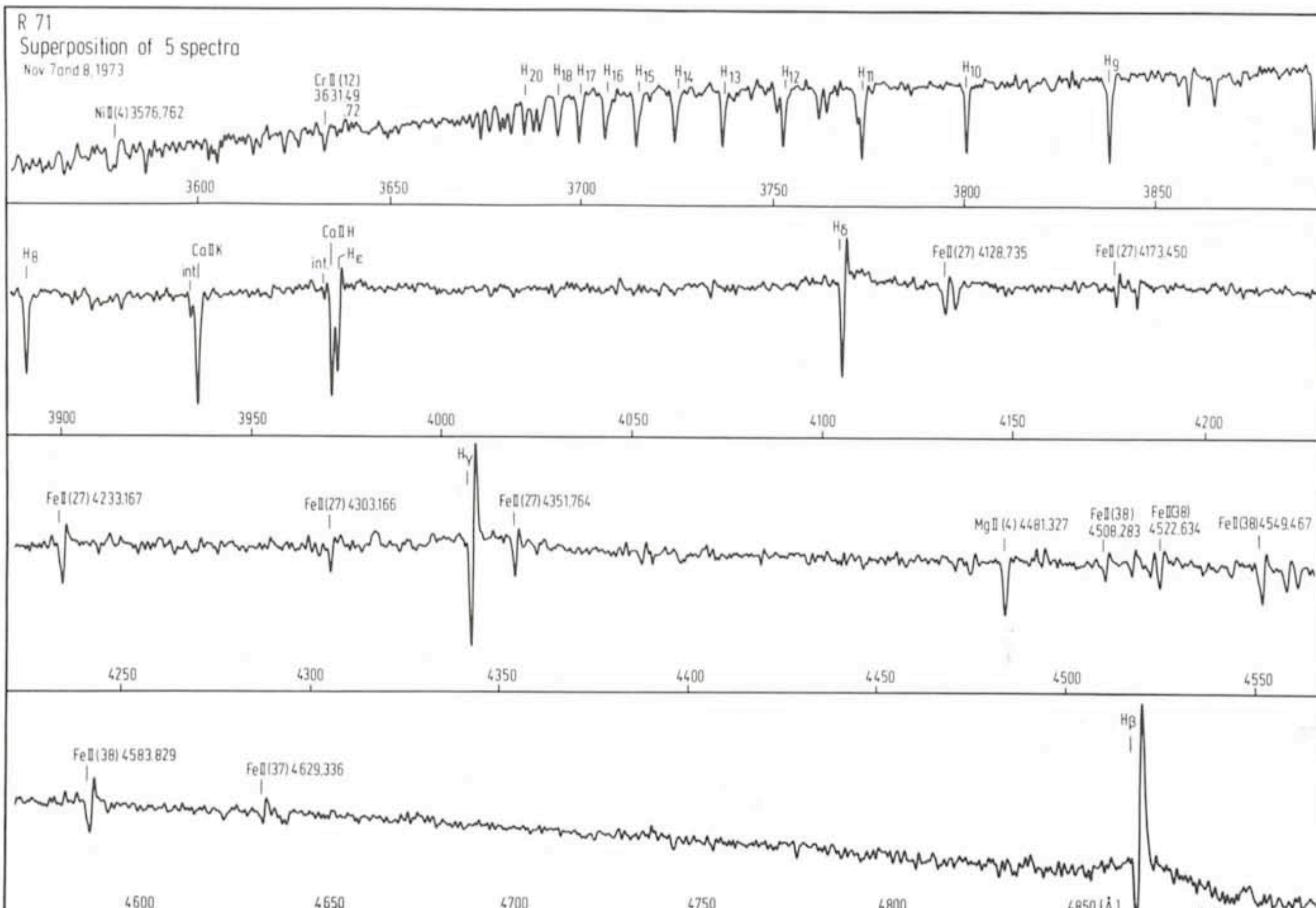

Fig. 3: *The photographic maximum state spectrum of HDE 269006.*

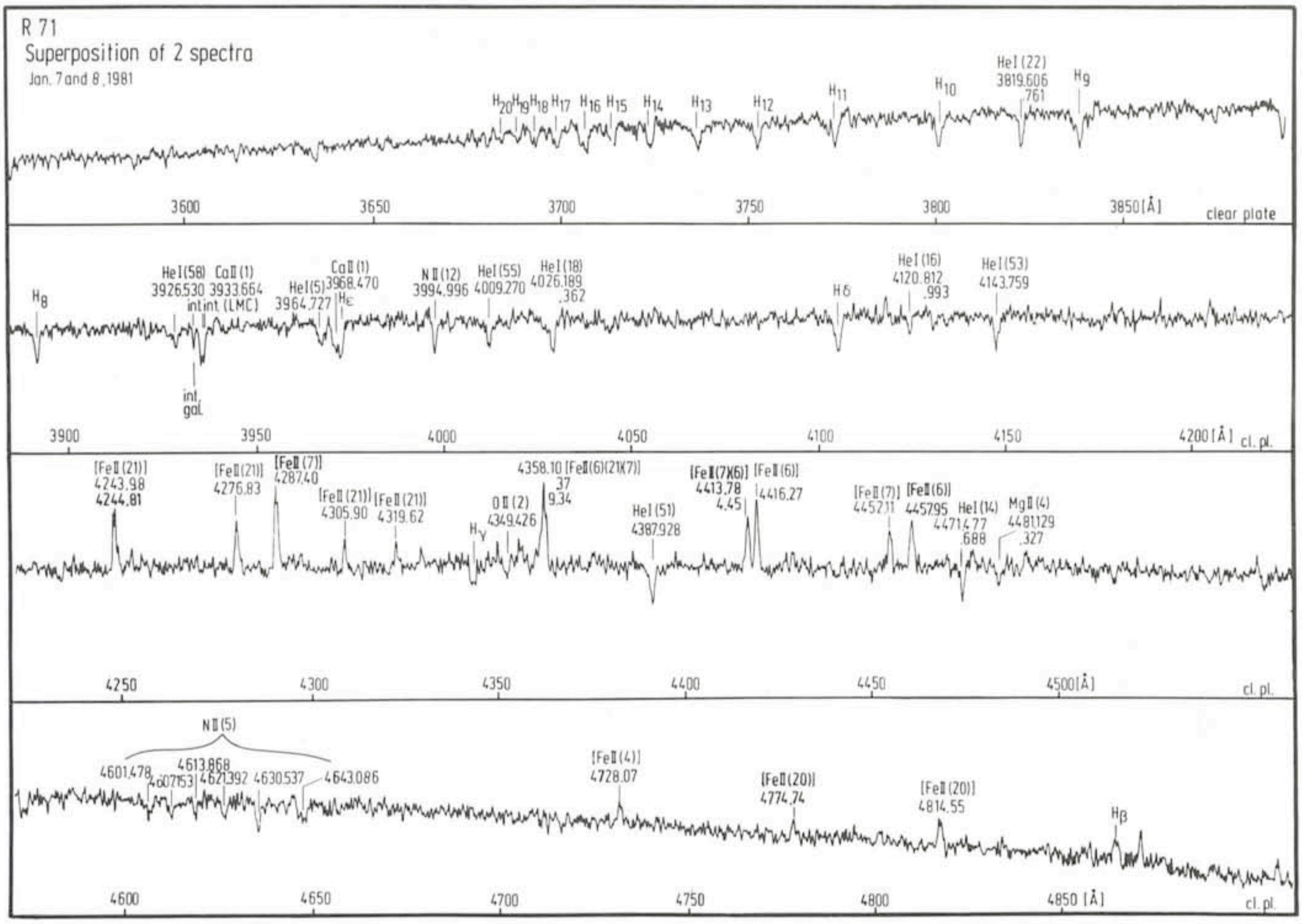

Fig. 4: *The photographic minimum state spectrum of HDE 269006.*

14,000 K). Although the luminosity quoted above is huge, it is considerably lower than had been expected from ground-based observations alone. In part this difference is due to the (for a B 2.5 star) relatively low effective temperature. However, more important is the fact that as a result of numerous broad envelope absorption lines of many different ions, the ultraviolet flux of R 71 was found to be much lower than expected.

In passing we note that for the derivation of the total luminosity and effective temperature we first had to estimate the total light extinction by interstellar dust along the line of sight to R 71. From earlier ground-based observations of distant galactic stars and "normal" LMC stars the galactic foreground extinction in the direction of R 71 was known to be relatively small ($E_{B-V} \approx 0.05$). However, the additional extinction occurring inside the LMC was unknown. Although our spectroscopic observations did not allow to detect this dust extinction directly, we were able to observe many interstellar absorption lines produced by the interstellar gas in the LMC. Because of the orbital motion of the solar neighbourhood around the centre of our galaxy, these lines are redshifted compared to their galactic counterparts and can therefore be separated on high-resolution spectrograms. As illustrated by Figure 2 (and also by the λ 2599 line, Figure 5) the LMC interstellar lines were always found to be weaker than those produced in our galaxy, indicating that along the line of sight to R 71 there is even less interstellar matter in the LMC than in our galaxy.

A second important result of our observations concerns the properties of the circumstellar envelope of R 71, as derived from the UV and visual line spectrum: In Figure 3 and 4 we give, respectively, the maximum state and the minimum state line spectrum in the wavelength range 3550 to 4900 Å. (The maximum state spectrum was observed by M. de Groot in 1973 and will be described in detail in a forthcoming publication by Stahl, Bastian, de Groot, and Wolf.) Both spectra reproduced in Figures 3 and 4 are based on coudé plates obtained at ESO, with the same equipment, and all plates were reduced in the same way. As shown by Figure 3, the maximum state spectrum is dominated by *emission* lines of hydrogen and the permitted multiplets of Fe II, Cr II, Ni II, etc. All emission lines show pronounced "P Cygni line profiles" (i.e. absorption components bluewards of the emission peaks). In addition there are blueshifted strong absorption lines (like the Ca II H and K lines). The P Cygni line profiles and the 3 blueshifted absorption lines are obviously produced in matter moving away from the star, i.e. in the expanding circumstellar envelope. The (rather weak) high excitation He I, Mg II, and Si II lines, which are formed in the deeper layers of the photosphere, are unshifted.

At minimum light (Figure 4) the blue-visual spectrum of R 71 looks highly different: In the whole spectral range reproduced, there is no line showing a P Cygni profile, and the once dominant permitted Fe II, Cr II, and Ni II emission lines are undetectable or extremely weak. Instead, the (unshifted) high excitation photospheric lines are now rather conspicuous in absorption. In addition, the spectrum now is dominated by *forbidden* [Fe II] emission lines of considerable strength (although such lines are undetectable in the maximum state spectrum). However, the greatest surprise came when we looked at the high-resolution IUE spectrograms obtained simultaneously with the spectrum reproduced in Figure 4. As illustrated by Figure 5, in the far ultraviolet part of the spectrum, permitted Fe II lines are still present (and in fact quite strong) and show beautiful P Cygni line profiles! Other sections of the UV spectrum contain many more P Cygni profiles or blue-shifted absorption lines of many different ions ranging from Mg I to C IV, proving that the outflowing circumstellar envelope is still present in the minimum state. However, a closer look showed that only envelope lines of relatively low excitation potential could be detected (throughout the spectrum). From a comparison of the different line strengths we found for the envelope a rather cool excitation temperature of only about 6,000 K. This obviously explains the absence of the permitted metallic lines in the photographic minimum state spectrum, since all these lines in the photographic wavelength range originate from energy levels not significantly populated at such low temperatures.

Since forbidden lines are emitted only from highly rarefied gases, it is clear that the [Fe II] lines shown in Figure 4 must originate at a considerable distance from the stellar photosphere. A simple analysis of the observed line strengths indicates for this region a distance of about 100 stellar radii. Therefore, we can use the width of the [Fe II] lines to estimate the expansion velocity of the envelope at this distance to 78 $\pm$ 6 km s^{-1}. On the other hand, from the P Cygni profiles (which can be formed only within a few stellar radii from the star) of the permitted UV Fe II lines, we can estimate the expansion velocity close to the stellar surface to about 127 km s^{-1}. Thus, R 71 seems to have a *decelerated* expanding circumstellar envelope, which is thought to be rather unusual for luminous early-type stars. By comparing the observed P Cygni profiles of the Fe II lines to model computation we furthermore estimated the minimum state mass loss rate of R 71 to 3×10^{-7} solar masses per year, compared to a maximum state mass loss of the order of 5×10^{-5} solar masses per year. On the other hand, we found the expansion velocity of the envelope to be about the same at maximum and minimum state. This can be understood only under the assumption that the density of the envelope at maximum light is higher by a factor of the order of 100 or more. This suggests that the density of the circumstellar envelope is probably the main difference between the minimum and maximum state of R 71. The higher visual brightness of the maximum state would then simply be due to the fact that more of the photospheric ultraviolet radiation is absorbed by the envelope and reradiated at visual wavelengths. An excellent test of this hypothesis would be a direct comparison with IUE spectrograms of R 71 obtained at maximum state. Unfortunately, as noted above, the last maximum had just ended when the IUE satellite was launched, and a comparison of the average duration of the minimum state of R 71 and of the estimated life expectancy of the IUE satellite makes it questionable whether such observations will ever become possible.

Applications for Observing Time at La Silla

Period 29

(April 1 to October 1, 1982)

Please do not forget that your proposals should reach the Section Visiting Astronomers **before October 15, 1981.**

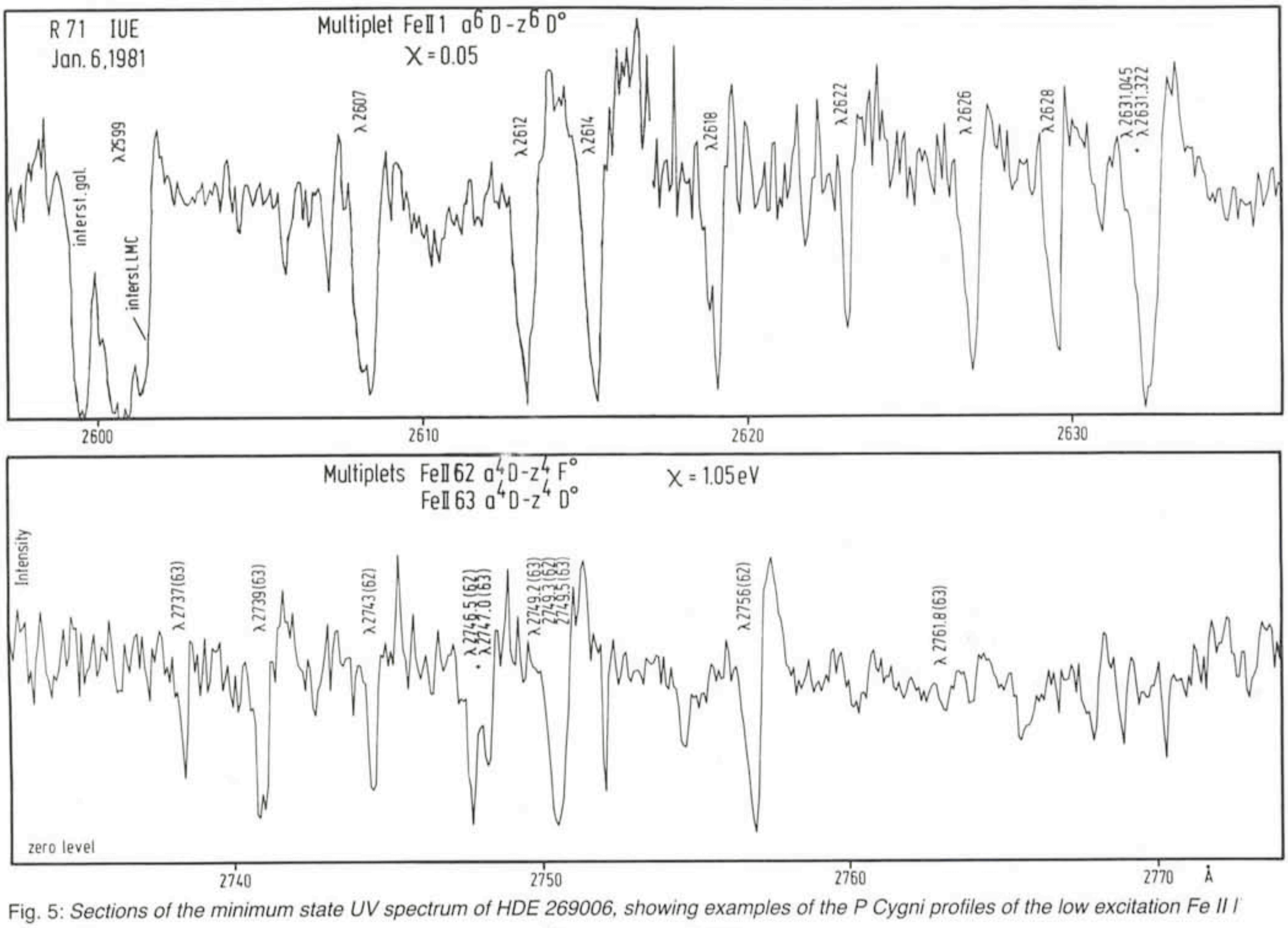

Fig. 5: *Sections of the minimum state UV spectrum of HDE 269006, showing examples of the P Cygni profiles of the low excitation Fe II l*