Long-term Photometric Campaign at ESO and the New Eclipsing P Cygni Star R 81 in the LMC

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1. A Programme for Long-term Photometry of Variable Stars

At the ESO workshop *The Most Massive Stars* in November 1981 (Eds. D'Odorico, Baade and Kjär), C. Sterken presented results of his observations of HD 160529 during a time span of more than 8 years. HD 160529 is an A2 hypergiant which was found to be variable by Wolf et al. (1974) in an irregular way with an amplitude of several hundredths of a magnitude. Sterken continued the monitoring of this star at every possible occasion in the period 1973–1981 and found evidence for the presence of periodic light variation of about 100 days. From the phase diagram he concluded that in spite of the intensive observations by one person, there still remain long gaps in the phase diagram. If sampling of observations happens in such an irregular way (gaps caused by irregularly allocated short observing runs), long-term orbital effects may be hidden by or ascribed to the supergiant's irregular intrinsic fluctuations. It was therefore suggested that the observations of e.g. variable supergiants be done by a larger team of observers at a dedicated small instrument. Such an approach would also be very useful for all differential photometry on a basis of one measurement per night or less: supergiants, Be stars, Ap stars . . .

During the discussions following the talk, several colleagues expressed their interest in the idea, and by the end of the Workshop, the project *Long-term Photometry of Variables* was born. In February 1982 a meeting was held at the University of Brussels, and the project finally started with an application for observing time submitted in April 1982. The participants (originally about 15) merged the objects for which photometry on a long-time basis was needed into one object list of about 70 entries, and then the file was split in seven sections according to the nature of the variable stars (see Sterken, 1983). Later on, an eighth section (Peculiar Late Type Stars) was added. For each section a principal investigator and a co-investigator were appointed. These scientists decide about which objects need monitoring, and they carry out and/or supervise the analysis of the data of the stars belonging to their sections. We agreed that the observers would be volunteering participants who work in a tight team with the principal investigators. From the beginning we aimed at obtaining several months of observing time each observing season, and this for a time span of at least one decade.

A project of that size, including the interpretation of measurements obtained at different telescopes and by different observers cannot work without a strict agreement on observing procedures and reduction techniques. Especially for what concerns the data reduction, high requirements are needed so that the final data may be of the highest obtainable accuracy. It was decided that all reductions would be done centrally (and not by the individual observers) at the University of Liège by J. Manfroid. The reduction algorithm is a generalized method developed by Manfroid and Heck (1983) and is characterized by the use of practically every measurement of any non-variable star. In doing so, all measurements are transformed into a standard system and the observations obtained during different seasons and with different instruments can be re-evaluated regularly so that the homogeneity of the data is assured.

Because of the availability of the suitable photometers on the ESO 50 cm and the Danish 50 cm telescopes, and for the usefulness for astrophysical interpretation of the data, we decided to carry out all measurements in the Strömgren uvby system. Since we deal with variable stars, preference was given to differential measurements with two comparison stars (although we have also carried out absolute measurements).

In practice the participants may expect to receive their data not later than three to six weeks after termination of the observing run. Since 1982 the number of participants has doubled, and this is also so for the number of stars. At least 30 stars, for which enough data were obtained, have been omitted from the object list. 26 observing runs with a duration of about one month length each have already been allotted by ESO and a huge amount of data are already available. The results have already led to more that 20 published scientific papers.

The nature of some discoveries (like e.g. the binary nature of R 81 which is described below) clearly proofs that this approach is a very efficient and useful one. Besides the direct yield of data, the project also offers to young scientists (e.g. Ph.D. students) the possibility to get into contact with the fields of research of the other participants, which substantially contributes to their observational experience.

2. R 81, the Counterpart of P Cyg in the LMC

P Cygni is one of the most outstanding stars of the Galaxy. It had a remarkable outburst in 1600 and is particularly distinguished by its unusual spectrum. The so-called P Cygni profiles in the visual range (which have been discovered already in the 19th century) are named after this prototype and indicate that this star is losing mass at an excessive rate. P Cygni belongs to the luminous ($M_{bol} \approx -9$ to -11) blue variables (LBV's) which have been recognized during the past few years as key-objects for the understanding of the evolution of the very massive (initial masses $\geq 50\ M_{\odot}$) stars. According to current evolutionary models (cf. e.g. Humphreys 1986, Chiosi and Maeder 1986) these very massive stars do not become red supergiants; instead a critical luminosity boundary exists (called Humphreys Davidson limit) beyond which the most luminous stars do not evolve. The LBV's are located close to this boundary and are supposed to be the immediate progenitors of the Wolf-Rayet stars.

The physical properties of P Cygni have been scrutinized during the past few years at a wide wavelength range from the UV with IUE to the IR with IRAS! A drawback of P Cygni is that both its interstellar reddening and its distance are difficult to determine (see e.g. Lamers, de Groot and Cassatella 1983). For this reason we searched the zoo of the luminous blue supergiants of the Large Magellanic Cloud (LMC). As outlined e.g. in our recent atlas of high dispersion spectra of luminous LMC stars (Stahl et al. 1985) the P Cygni type stars form in fact a populous group among the peculiar emission line stars.

Already in 1981 Wolf et al. presented a detailed spectroscopic and photometric study of R 81 of the LMC. R 81 turned out to be a particularly close counterpart of the galactic star P Cygni.

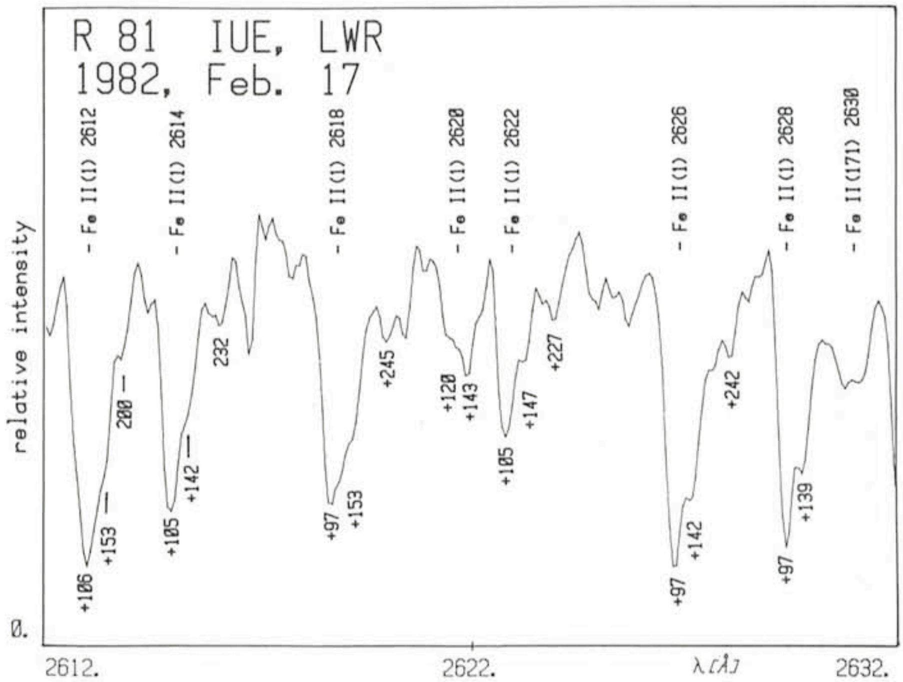

Figure 1: *A section of the IUE high-dispersion spectrogram around 2600 Å. This wavelength range is dominated by Fe II absorption lines. Like in P Cyg, different components are present. The velocities of these components are indicated for different lines.*

Both stars are (of course) characterized by strong P Cygni profiles of the Balmer lines and by very similar stellar parameters: $T_{eff} \approx 20{,}000$ *K*, $M_{bol} \approx -10$, and $R \approx 70\ R_\odot$ for R 81 and $T_{eff} \approx 19{,}300$ *K*, $M_{bol} \approx -9.9$, and $R \approx 76\ R_\odot$ for P Cygni (for the data for P Cyg see Lamers et al. 1983). They are located in the same part of the Hertzsprung-Russell Diagram (HRD) close to the Humphreys-Davidson limit. The winds of both stars are slow ($v_{max} \approx 250$ to $300\ km\ s^{-1}$) and very massive ($\dot{M} \approx 3 \cdot 10^{-5}\ M_\odot\ yr^{-1}$ for R 81 and $\dot{M} \approx 1.5 \cdot 10^{-5}\ M_\odot\ yr^{-1}$ for P Cyg). Like P Cyg (Waters and Wesselius 1986) R 81 is surrounded by a cool loosely bound dust envelope since Stahl et al. (1987) identified R 81 as an IRAS point source. The dust formation could be a consequence of their slow and dense winds.

One of the most paradoxical results derived from the IUE spectrum of P Cygni (Cassatella et al. 1979) is that this hot star with its unusual P Cygni profiles in the visual range is right the other way distinguished by a lack of P Cygni profiles in the ultraviolet (which are otherwise so typical for hot stars in this range). Just this behaviour is found in the case of R 81 as well. Still more intriguing is the fact that e.g. the Fe II lines of both stars agree even in details. The complex profiles show a multiple component structure (for R 81 see Fig. 1) ascribed to the ejection of discrete shells (cf. Lamers et al. 1985 and Stahl et al. 1987).

In addition to the major historical outbursts of P Cygni in the 17th century, irregular photometric variations of 0.1 to 0.2 magnitude have been reported during this century by many authors. No strict periodicity has yet been found (van Gent and Lamers 1986). Likewise in the case of R 81, which until 1980 was repeatedly observed during various randomly distributed photometric observing runs, variations of about this amplitude are quoted. Wolf et al. (1981) regarded these variations as to be "of irregular nature rather than of a periodic one". Shortly after this the programme

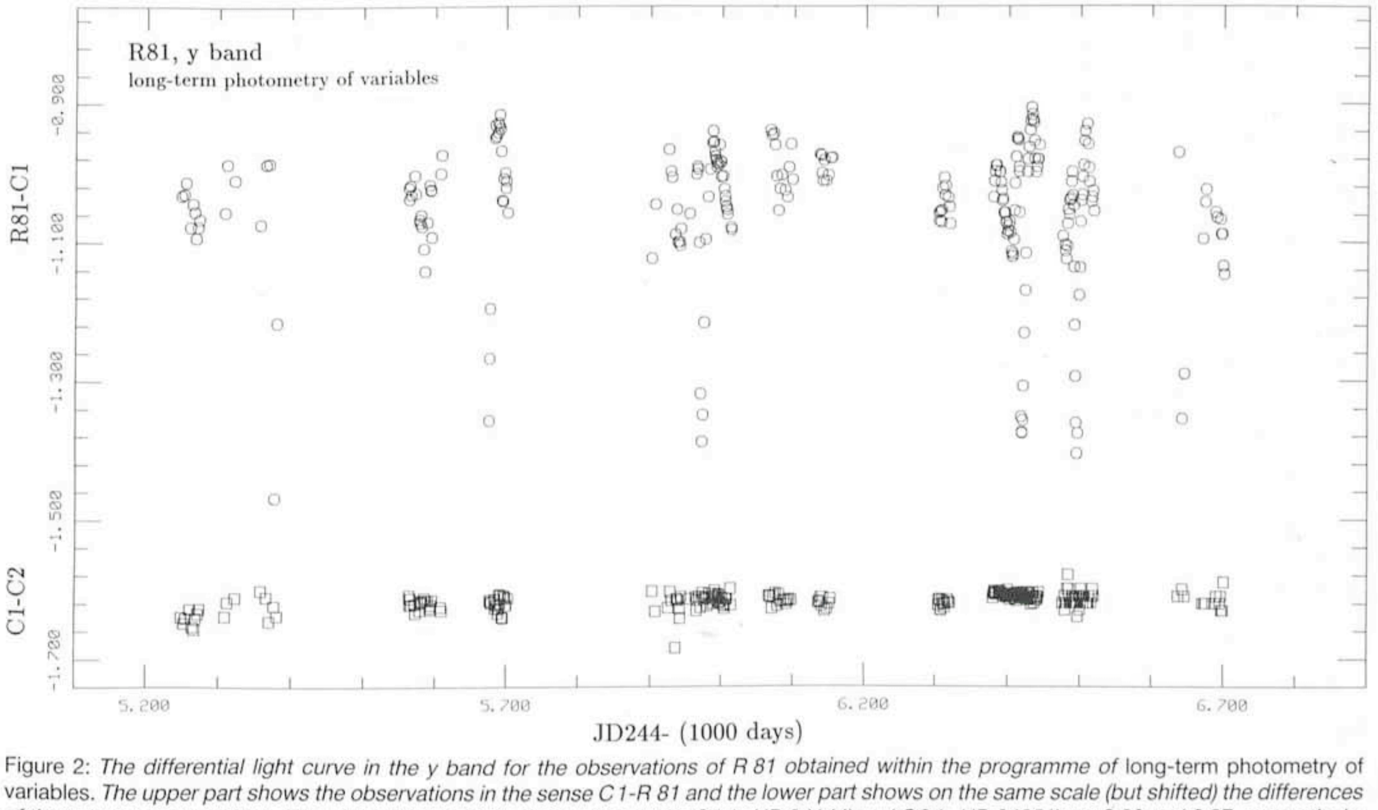

Figure 2: *The differential light curve in the y band for the observations of R 81 obtained within the programme of* long-term photometry of variables. *The upper part shows the observations in the sense C 1-R 81 and the lower part shows on the same scale (but shifted) the differences of the two comparison stars. The y magnitudes of the comparison stars C 1 (= HD 34144) and C 2 (= HD 34651) are 9.32 and 8.37, respectively. The scatter in the differences y (C 1-C 2) of the two comparison stars is 0.007 which documents the quality of the photometry.*

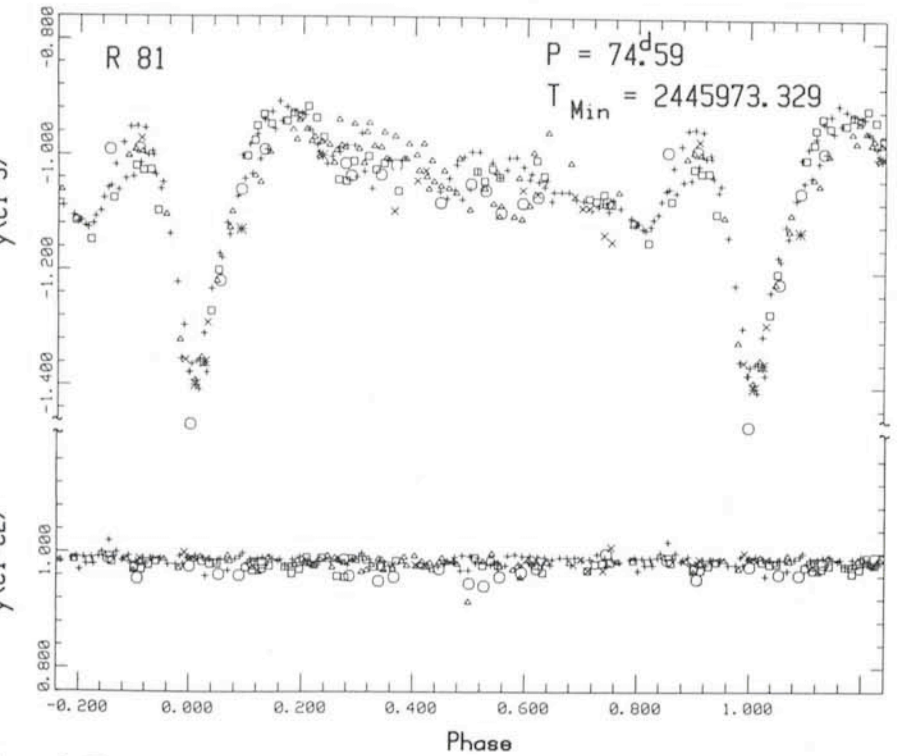

Figure 3: *The phase diagram of the data shown in Figure 2. In addition the V data of Appenzeller (1972) have been included. The different symbols denote observations performed during different observing seasons (○ for 1982/1983, □ for 1983/1984 △ for 1985/1986, + for 1985/1986 and × for 1986/1987. Appenzeller's earlier observations (JD 2441274 – 1292) are denoted by* ✱. *The period of the eclipses is particularly well defined due to the earlier observations of Appenzeller. The eclipse with a depth of 0.4 mag can clearly be seen. The shape of the light curve is particularly distinguished by the absence of a pronounced secondary minimum and by a pre-eclipse dip of 0.15 mag at phase 0.80.*

of *long-term photometry of variables* described above was initiated. Undoubtedly, a detailed knowledge of the time dependence of brightness variations is important for the derivation of a physical model for P Cyg stars. Since "P Cyg of the Galaxy" has obviously never been monitored during several years by high-precision photometry at sites with comparable excellent weather conditions as at La Silla, we included "P Cyg of the LMC" (i.e. R 81) in the long-term photometry programme at ESO.

3. The Eclipsing Binary R 81

R 81 was already found by Appenzeller (1972) to exhibit variations with the rather large amplitude of 0.4 mag within two weeks. We subsequently observed R 81 in several years in observing runs of about two weeks each, but we were unable to find a similar event. Only variations of about 0.15 mag, which seemed to be irregular, were found. So R 81 was regarded as an irregularly variable P Cyg star, although the time coverage was too incomplete to do a meaningful period analysis.

In the first three observing seasons of the long-term programme we had observed each year once that R 81 had faded far below its normal brightness. In addition, we found that the minima repeated every 300 days. At that point we realized that the variations of R 81 might be at least partly periodic and we decided to give this star a high priority in the further observations since never before had strictly periodic variations been found in a classical P Cyg star. Until now we have collected observations in 240 different nights distributed over a period of more than four years. The observations are shown in Figure 2. This data set was analysed with a period searching algorithm and we finally found that the period of the variations was about 74.6 days. With the period already known with some precision, the observations of Appenzeller (1972) could also be tied in. They then define the period particularly well since they extend the time base by more than ten additional years (which is about 50 cycles). Taking all data together, we obtain a period of 74.59 ± 0.01 days. The phase diagram of the y-band data which was constructed by using this period is shown in Figure 3. This phase diagram clearly implies that R 81 is an eclipsing binary. The light curve is very distorted which suggests that both components are in close contact.

Obviously, the detection of a binary P Cyg star is very important since we might hope to derive the parameters of the system, specifically the mass. This is a very important undertaking, since there are no direct mass determinations of a P Cyg star available. So far, we obtained two CASPEC spectra and one CES spectrum of R 81. A portion of the CASPEC spectra is shown in Figure 4. It is clear from this figure that most of the lines have a P Cyg profile or are blue-shifted absorption lines originating in the stellar wind of R 81. They are thus not very useful to determine the orbital velocity of the star. From the very few photospheric lines in the spectra we could so far not obtain a reliable radial velocity curve. In addition, no secondary spectrum has been found so far.

Luckily, some information can be obtained from the photometry: The absence of a pronounced secondary eclipse probably means that most of the visual brightness is supplied by one component. The depth of the eclipses suggests that the eclipsing body has a

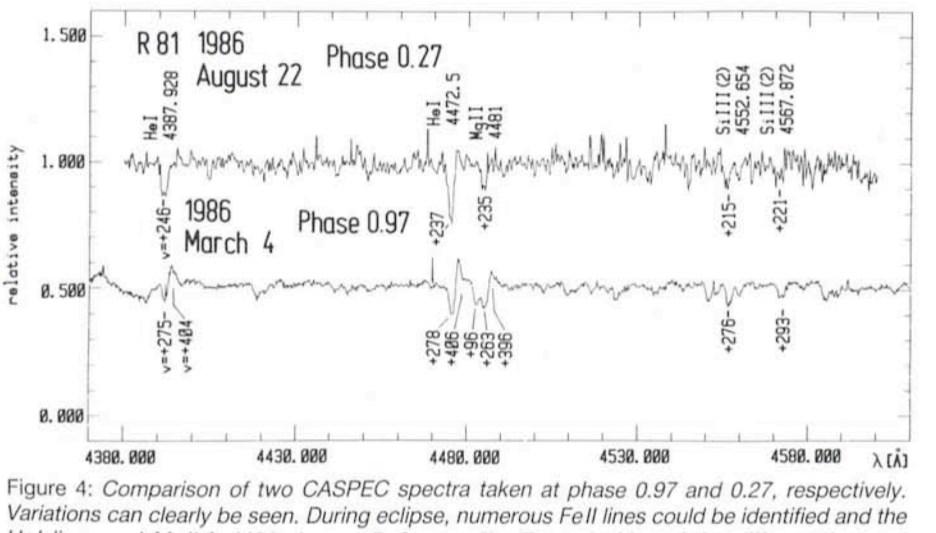

Figure 4: *Comparison of two CASPEC spectra taken at phase 0.97 and 0.27, respectively. Variations can clearly be seen. During eclipse, numerous FeII lines could be identified and the HeI lines and MgII λ 4481 show a P Cyg profile. The velocities of the different lines are indicated in the Figure.*

radius which is comparable to the radius of the visible star, which is known from the brightness, temperature and distance of R 81. The width of the eclipses of the star with respect to the period then allows us to estimate the distance of both stars from each other and thus from Kepler's third law (with the period) the total mass of the system. We find a mass of about 35 $M_\odot$ for R 81. This result is in good agreement with the expectations for a luminous P Cyg star, but note that it is the first direct mass estimate for such a star. We note that this mass estimate is very uncertain so far and clearly more spectroscopy is needed in order to confirm this result.

Interestingly, the scatter around the mean curve of Figure 3 is only of the order of 0.05 mag. This means that also most of the smaller variability which we observed between the eclipses is due to the changing aspects of the observations and not intrinsic to the star. This result leads to the suspicion that also other variations of R 81, e.g. the spectroscopic variations of certain stellar wind lines, are not irregular but phase-dependent. An important point to clarify is also the nature of the secondary. No obvious secondary minimum is present, so the star must be visually faint. New spectroscopic observations of high quality and good phase coverage are badly needed.

The more general question is, of course, whether many P Cyg stars are binaries. Our finding certainly does not prove this. However, the small scatter around the mean light curve shows that R 81 intrinsically is at most slightly variable. If other P Cyg stars (which are observed to be variable with relatively large amplitude) are similar to R 81 in this respect, then the variability observed in these stars requires an explanation.

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Blue Horizontal Branch Field Stars in the Outer Galactic Halo

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1. Introduction

It is a well-known hypothesis that galaxies are surrounded by extended massive envelopes of "dark" matter reaching far beyond the visible edges of the galaxies. For our own Galaxy this hypothesis is supported by kinematical and dynamical studies of globular clusters in the outer Galactic halo.

The usefulness of globular clusters as test objects for probing the mass distribution in the outer part of the Galaxy is limited, however, for the following reason: The sample is small – the number of globular clusters with Galactocentric distances between 15 and 40 kpc, which can be used in a kinematical analysis, is 14. Furthermore, several recent remeasurements of globular cluster radial velocities have shown some of these to be substantially in error.

Lynden-Bell, Cannon and Godwin (1983) studied a sample of dwarf spheroidals situated at very large Galactocentric distances ($\sim$ 100 kpc). They found the objects to have quite low line of sight velocities (relative to the Galactic restframe) – the line of sight velocity dispersion was found to be $\sim$ 60 km/s. Even if one assumes that the velocity distribution of these objects is isotropic, a mass of only $M = (2.6 \pm 0.8) * 10^{11}$ $M_\odot$ is inferred. This does not support the hypothesis that the mass of the Galaxy increases linearly with Galactocentric distance to distances $\geq$ 100 kpc.

In order to clarify further on the properties of distant halo objects we have identified and studied a sample of blue horizontal branch field (bhbf) stars in the outer Galactic halo ($r \leq 40$ kpc). The observations are described in section 2, and the results are discussed in section 3.

2. Observations and Data Analysis

We have carried out a search for bhbf stars at large Galactocentric distances. Part of the observations have been described in Sommer-Larsen and Christensen (1985 and 1986). The basic material was three stellar object catalogues, kindly provided by Drs. G. Gilmore and N. Reid. The catalogues cover three fields located at the SGP (l, b) = (38°, –51°) and (l, b) = (352°, 52°). In total the catalogues cover 54 square degrees of the sky, and they are complete to V = 18.5. By observing spectroscopically faint blue stellar objects drawn from these catalogues, using the selection criterion $0.0 \leq B\text{-}V \leq 0.2$, a sample of 131 bhbf star candidates have been obtained.

The observations were done with the ESO 2.2-m telescope during a number of observing runs in the period 1984–1986. The observational setup and procedure were the same during all observing runs: The detector system consisted of a Boller and Chivens spectrograph together with the dual Reticon Photon Counting System (RPCS) (Christensen et al., 1984). The two decker holes, each projecting down onto its own Reticon-array, corresponded to an area of $4*4$ arcsec^2. With a slit the aperture was reduced to 2 arcsec in the direction of dispersion. A 600 lines/mm grating blazed in the first order at 4200 Å was used yielding a reciprocal dispersion of $\sim$1 Å per channel. The wavelength range covered was