AG Carinae III.

The 1990 hot phase of the star and the physical structure of the circumstellar environment

R. Viotti\textsuperscript{1}, V.F. Polcaro\textsuperscript{1}, C. Rossi\textsuperscript{2}

\textsuperscript{1} Istituto di Astrofisica Spaziale, CNR, Via Enrico Fermi 21, I-00044 Frascati RM, Italy
\textsuperscript{2} Istituto Astronomico, Università La Sapienza, Via Lancisi 29, I-00161 Roma, Italy

Abstract. We report new long slit blue and red spectra of the region around the Luminous Blue Variable AG Car obtained at ESO in June 1990. The spectroscopic observations of the central star, observed just before the onset of its new brightening phase, indicate that AG Car was in the hottest phase so far recorded. The spectrum shows strong Balmer emission lines, and broad emissions of He\textsc{ii} λ468.6, and [Fe \textsc{ii}] λλ465.8-470.1, as well as many lines of He\textsc{i}, N\textsc{iii}, Si\textsc{iii}, Al\textsc{iii} and Fe\textsc{iii} with a P Cygni profile. The [N \textsc{ii}] red doublet is present in the wings of H\textalpha. We have also identified weak emission lines of C \textsc{ii} and, for the first time, of O \textsc{ii} with a P Cygni profile.

The nebula was observed with the slit centered on the star, and displaced by ±5 and ±10 arcsec in declination. All fluxes of the nebular lines (H\textalpha, [N \textsc{ii}], [S \textsc{ii}]) peak in the ring. The mean electron density is n\textsubscript{e} = 580 cm\textsuperscript{-3}. We also find that the spectrum of some regions 5 North and South of AG Car is partially due to scattered star’s light. This provides further evidence of the presence of dust grains close to the central star, and indicates that even in present times dust is condensing from AG Car wind. A faint nearly uniform continuum emission has been detected for the first time within the whole ring nebula which we again associate with the presence of dust. The existence of an effective dust condensation process in the wind of AG Car should largely affect the chemical abundance of the nebula. The sharp outer edge of the ring might suggest the presence of a shock front.

We have finally identified an extended low density (n\textsubscript{e} = 180 cm\textsuperscript{-3}) H\textsc{ii} halo, which should be associated with the residual of the stellar wind of a previous, probably cooler, evolutionary phase of AG Car. In the halo the Ha/[N \textsc{ii}] ratio is strengthened with respect to the ring nebula, possibly because of a discontinuity in the N abundance. The relative line strengths in the ring and halo are those typical of large PNs and H\textsc{ii} regions, respectively. We suggest that part of the star’s reddening originates in the circumstellar ring nebula and diffuse halo, which could substantially alter the present estimates of the star’s distance.

Key words: stars: circumstellar matter – stars: emission line – stars: individual (AG Car) – stars: mass loss

1. Introduction

AG Car (= HD 94910), together with η Car and P Cyg, is one of the few well established galactic Luminous Blue Variables (LBVs). These objects are believed to be a short-living (10\textsuperscript{3}-10\textsuperscript{9} years) phase of the high mass (M\textsubscript{⊙} > 40 M\textsubscript{⊙}) stars evolution, immediately preceding the WR phase. In spite of its many peculiarities, such as the prominent emission line spectrum, the ample light variations, and the presence of a ring nebula, AG Car has been only in recent times the subject of systematic studies. The star shows a large variability (between 6\textsuperscript{m} and 9\textsuperscript{m}) with time scales of the order of many years, and with superimposed erratic variability of around 0.5\textsuperscript{m} (e.g. Nota et al 1992 and references therein). Caputo and Viotti (1970, Paper I) found that the luminosity variations of the star are accompanied by dramatic spectral changes, from equivalent spectral type A1 I to B0 I, being the star hotter near its visual light minima. During 1981-1985 AG Car underwent a large luminosity fading in the visual, which was accompanied by conspicuous spectral changes, both in visual and ultraviolet wavelengths (Wolf and Stahl 1982, Viotti et al. 1984, Stahl 1987). Viotti et al. (1984) showed that the visual fading after 1981 was accompanied by a corresponding increase in the UV flux, so that the total bolometric luminosity remained constant. This is an important result which was later found in other LBVs. Stahl (1986) found that the spectral type of the star during the January 1985 minimum was similar to that of intermediate Ofpe/WN9 stars. A new brightening phase started in 1990 with an increase of the visual and IR luminosity (Mattei 1992, Whitelock 1992), and marked spectral variations (Leitherer et al. 1992). In both minimum and maximum luminosity states, the star is characterized by a rich emission line spectrum. Variable P Cygni profiles have been detected in different epochs in Hydrogen Balmer, He\textsc{i}, and Fe\textsc{ii} lines. This fact, as well as the presence of many forbidden lines in the spectrum of the star is an indicator of an extremely complex and variable structure of the stellar envelope.

A key characteristics of AG Car is its surrounding ring nebula which has revealed in recent times many peculiarities. This

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nebula, named 289–0°.1 in the Perek and Koutek (1967) catalog of planetary nebulae, was probably ejected by AG Car (e.g. Thackeray 1977, Stahl 1987, Viotti et al. 1988, Paper II). Its UV spectrum is similar to that of the central star, suggesting that dust grains are scattering the star’s light (Viotti et al. 1988); this hypothesis was also supported by the far-IR KAO observations (McGregor et al. 1988b). Paresce and Nota (1989) discovered an inner dusty jet-like feature with a possible helical structure. Smith (1991) and Nota et al. (1992) studied the nebula dynamics and found that the radial velocities are consistent with a hollow expanding asymmetrical shell.

Thus, the studies performed up to now on AG Car have supplied a large amount of experimental evidences that can be used to clarify the LBV evolutionary phase of very massive stars. On the other hand, some crucial points are still obscure and need to be clarified in order to model the physical conditions of the object. For instance, the distance of AG Car is still poorly determined. Up to a few years ago, the star was believed to belong to the Carina OB associations and its distance was thus estimated to be about 2.5 kpc (Viotti 1971) the same as that of the Trumpler 14 and 16 associations (e.g. Tapia et al. 1988). Recently, Humphreys et al. (1989) and Hoekzema et al. (1992) suggested a much higher value (5 to 8 kpc) on the basis of more recent kinematic and luminosity data of field stars. According to this value AG Car should have an absolute bolometric luminosity of about $-10^4$, in good agreement with that of the other LBVs near the Humphreys and Davidson (1979) instability track. This would also imply that the evolutionary track of the star should have never reached the red supergiant phase.

Another problem that is far to be solved is the origin and thermal balance of the dust grains which are present in the nebula. Far-IR data indicate that the dust grains should be cool (60 K) and composed by large (~1 μm) grains (McGregor et al. 1988b), in order to survive so close to a very luminous hot star. This fact suggests that the dust nebula must be old, possibly a remnant of a previous cooler evolutionary phase of the central star, in order to have enough time for large grains be formed. On the other hand, the colours of the ‘jet’ strongly support the hypothesis that it is mainly composed of dust grains (Paresce and Nota 1989, Nota et al. 1992). Nota et al. (1992) have analyzed the possible formation of the dust as due to the presence of an equatorial disk due to the stellar rotation or to a close, undetected companion. Neither hypotheses are fully convincing because of the lack of other detectable effects generally associated with these models, such as line splitting, short term periodicities, and hard-X ray emission. We remind that the unexplained dust formation around very hot objects (like WR stars) is not an unusual problem (Conti and Underhill 1988), and that only in a few cases this effect can be explained by the presence of a companion (Williams and van der Hucht 1991). In most of the reported cases, these dusty nebulosities are asymmetric.

A further unsolved problem concerns the chemical composition of AG Car and of its nebula. The evolutionary models (e.g. Maeder 1990) indicate that a LBV should be overabundant in nitrogen. In fact, a N/C overabundance in the star spectrum could be suggested by the strength of the N II lines during the Be phase and the contemporaneous undetectability of C II and O II lines (Caputo and Viotti 1970). In the IR, no molecular emission from CO was found by McGregor et al. (1988a), whereas it was detected in the similar object HR Car. Mitra and Dufour (1990), from the study of the spectrum of the nebula derived a high N/CO ratio in the nebula which they attribute to a marked CO underabundance, while the N should have a normal abundance. Whereas, Pacheco et al. (1992) found that nitrogen actually is overabundant by one order of magnitude and oxygen deficient by at least a factor 6. Nota et al. (1992) argued that the abundance anomaly in the nebula can be explained if the outburst that originated the nebula have occurred at the beginning of the LBV phase, when the chemical composition was not too changed with respect to the previous phase. This explanation is supported by the similarity of the figures of the dynamical age of the nebula ($10^4$ to $10^5$ y, Viotti et al. 1988; Smith 1991) and of the LBV-phase duration ($10^4$ y, Humphreys 1989). However, it is difficult to explain why in one LBV (AG Car) the main outburst occurred at the beginning of the phase, while in the others (η Car and P Cyg) it seems to have occurred at a much later stage.

In this paper we report new long slit spectroscopic observations of AG Car and its nebula, made when the star was at a crucial phase of its light history.

2. Observations

We have observed the blue (433-487 nm) and red (620-727 nm) spectrum of AG Car and of its surrounding nebula in June 1990, just before the onset of the recent new brightening phase of the star (Whiteock 1992). Two dimensional spectra were obtained at the Cassegrain focus of the 1.52 m ESO telescope equipped with the Boller & Chivens spectrograph and a GEC coated CCD 576×370 pixel detector. A 850 grooves mm$^{-1}$ grating was used, giving a resolving power of 0.18 and 0.36 nm (FWHM) in the blue and red ranges, respectively. Excellent seeing (better than 1 arcsec) during the whole observing run allowed the use of a 1 arcsec slit width. The slit was 3.0 arcmin long, oriented in the E-W direction. Spectral images were taken with the slit centred on the central star, and 5 and 10 arcsec to the North and to the South. The slit positions were accurate in declination within ±1 arcsec, as also checked a posteriori from the presence in the images of nearby stars which were identified from the direct images. The standard stars Wolf 485A and Kopf 27 were used for flux calibration. Table 1 reports the detailed log of the observations.

The columns of the CCD images were binned during the reading process, and the final data are recorded as 576×103 images with a spatial scale of 1.0 arcsec per pixel in the dispersion direction, and 2.0 arcsec per binned pixel orthogonally to it. The whole 3 arcmin slit length corresponds to 90 binned columns. In the dispersion direction one pixel corresponds to 0.09 and 0.18 nm in the blue and red spectral images, respectively. The effective spectral resolution is of 2.0 pixels.

The images were reduced with the VAX 8550 of the Istituto di Astrofisica Spaziale using standard procedures for background subtraction and flat-field correction. Then one-dimensional spectrograms were extracted by adding up three adjacent columns – corresponding to an effective projected area of 6×1 arcsec$^2$ – centered on the odd columns for a total of 45 spectrograms for each frame.

In order to take into account the small distortion along the detector, the wavelength calibration were performed using a polynomial approximation on each extracted spectrogram of the He-Ar comparison lamp. This pixel–to–wavelength rela-
tionship was applied to the corresponding columns of the object spectrograms. After wavelength calibration, the extracted spectrograms were corrected for the atmospheric extinction and for the response curve of the night in order to obtain absolute fluxes. The major problem of the reduction procedure was represented by the sky subtraction in the nebular spectra. For extended sources the sky subtraction is often difficult, especially in the red, as sky and nebular emissions are mixed up. In our case many intense sky lines are visible in the 10 min red exposures. Since the nebular emission lines are still visible at the edges of the field, we could not use these regions for the sky subtraction. This is illustrated in figure 1 where the red spectrum of the AG Car nebula near the field edges, and the sky spectrum in the field of one standard star, are compared. This comparison also shows that the underlying continuum in the AG Car nebular spectrum is mostly telluric in origin. The accurate subtraction of this effect has enabled us to find out the true nebular continuum near the star. Note that the presence of sky emission lines around Hα could be a cause of error especially in the extracted spectrograms far from the centre of the nebula, where the nebular emissions become quite weak. This was found particularly worrysome for the [N II] lines.

Having used the same exposure time for the AG Car nebular spectra and for one of the standard stars, and thanks to the excellent sky conditions, the sky line and continuum emission resulted to have the same intensity in the two sets of data. Therefore the following sky subtraction procedure was performed: for both the standard star and nebular frames we have verified that the intensity of the sky lines was constant along the frame columns; then we have obtained a mean sky spectrum of the standard star by averaging 10 spectrograms (5 for each side of the star); finally we have subtracted this spectrum from the extracted spectrum of the AG Car nebula. As shown in figure 1, the result seems to be quite satisfying. No local sky lines are visible in the less exposed red spectra centred on the star and in the blue images. Thus, no sky subtraction has been performed for these spectrograms.

From the cross-check of the flux calibration obtained using the two standard stars we are confident of an uncertainty of 10% for the absolute fluxes in the blue region, and of a somewhat larger value in the edge regions. In the red only one standard star has been taken exactly in the same spectral region. However, during the observing run we have observed other targets in the same red range of AG Car and in adjacent regions which partially overlap with the red one (e.g. Polcaro et al. 1992). Since we have found that the calibrated spectra are in good agreement in the overlapping regions, we are confident that the accuracy for the red spectrum of AG Car and its nebula should be comparable to that above derived for the blue region.

In the red and blue spectrograms the noise has been measured to be $1.3 \times 10^{-19}$ W m$^{-2}$ nm$^{-1}$ ptp in the nebular spectra. On the star the S/N ratio is 45 in the red continuum at 630 nm and 24 in the blue continuum at 440 nm. Referring to the lines the S/N ratio obviously depends on the line intensity; for instance we find S/N=132 at the Hα line peak, and 50 at the He I λ447.1 line peak.

3. Analysis of the results

3.1. The star

The spectrum of AG Car was measured on the central extracted spectrogram of the CCD frames centred on the star. The calibrated spectra in the blue and red regions are shown in Figure 2. Line fluxes were measured following the procedure described in previous articles (e.g. Polcaro et al. 1992, Viotti et al. 1989), and the results are reported in Table 2 where the successive columns give: (1) Heliocentric line barycentre (in nm). (2) Type of the line: absorption (A) or emission (E). (3) Total width of the line. (4) Line equivalent width (in nm); "p" = line present but not measurable. (5) Adopted continuum level in $10^{-16}$ W m$^{-2}$ nm$^{-1}$ (i.e. $10^{-14}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$) local to the feature, not corrected for the interstellar absorption. (6) Identification of the ion contributing to the observed line; (7) Laboratory wavelength. (8) Remarks: "PCy" = P Cygni violet-shifted absorption; "i.s." = interstellar line; "bl" = blended with the nearby line; "br" = broad line; possible contributors are also indicated.

Our observations were performed in an important phase of the star light curve since at the time of our observations AG Car was near minimum luminosity (Mattei 1992), and a few days later it started to brighten again, both in the visual and in the IR (Mattei 1992, Leitherer et al. 1992, Whitelock 1992). Our spectrum is characterized by the presence of very intense Hα, Hβ and Hγ emission lines, strong He i lines with P Cygni profile, and of emission lines of He i λ468.6 nm and [Fe II] λλ465.8 and 470.1 nm definitely broader than the instrumental profile. In addition, we have identified P Cygni lines of Si iii, Al iii, Fe iii, and especially of N ii (Fig.2). The optical spectrum of AG Car also shows weak lines of O ii λλ464.9, Si ii λ637.1, and C ii λλ723.1-723.6. The underlying continuum is rather flat, in agreement with the fact that AG Car is a highly reddened blue star. The B and V magnitudes, as

Fig. 1. Example of the red spectrum far from the ring nebula of AG Car. Top: the original spectrum; middle: the 'sky' spectrum; bottom: the sky-subtracted spectrum. The original and 'sky' spectra have been vertically shifted of 1.5 and 0.5 respectively. Or dinates are AG Car. Top: the original spectrum; middle: the 'sky' spectrum; cut in order to avoid overlapping of the tracings.
estimated from the continuum energy distribution, are \( \sim 9.1 \) and \( \sim 8.6 \), respectively. Whereas the colour index is in agreement with the stellar colour excess reported in the literature, the visual magnitude is a few tenth of magnitude fainter than that reported by AAVSO for the same period. This discrepancy could be partly attributed to the calibration error, and partly to a not negligible contribution of the emission line flux to the broad band photometry. We cannot anyhow rule out the possibility that AG Car was observed during a deep visual luminosity minimum.

Fig. 2. (a) The blue spectrum of AG Car in June 1990. (b) The red spectrum of AG Car observed in June 1990. (c) Enlargement of the blue spectrum to show the different profiles of the He I, He II, N II and [Fe III] lines. Ordinates are monochromatic fluxes in \( 10^{-14} \) W m\(^{-2}\) nm\(^{-1}\), not corrected for the interstellar extinction.

No blue-shifted absorption component has been observed in the Balmer lines. Actually, the disappearance of the P Cygni absorption in H\(\alpha\) during the hotter phase of AG Car was already noted by Bandiera et al. (1989), and should be associated with the increased ionization of hydrogen. Since H\(\alpha\) is saturated also in the lower exposed red spectrum, we cannot make an estimate of its intensity. The H\(\gamma\)/H\(\beta\) flux ratio of 0.37 (uncorrected for the interstellar extinction) is very similar to that measured in the ring nebula as discussed in the next section. This value is also in agreement with the value for the 1984 spectrum of AG Car found by Mitra and Dufour (1990), in spite of the different photometric phase of the star. This fact not only confirms that the contribution of the dust to the extinction in the optical wavelengths is small (McGregor et al. 1988b, Mitra and Dufour 1990), but also that it is not variable with the time or with the photometric stage of the star.

The He II line presents a remarkable round-topped shape with a FWHM, corrected for the instrumental profile, of about 220 km s\(^{-1}\) (Fig. 2c). Its strength indicates that at the time of our observations AG Car was in a somewhat hotter phase than that observed in 1985 (Stahl, 1986). The high temperature phase is also marked by the large number of emission lines of highly excited species. The N III 463.4-464.2 nm multiplet, which is characteristic of Of stars, if present, is masked by the many strong N II lines (Fig. 2c). This ion was not present in the Stahl’s 1985 spectrogram. The [N II] doublet is present in the wings of H\(\alpha\) (Fig. 2b).

A rich N II emission spectrum was previously observed in the spectrum of AG Car during the high excitation phase of 1953-1955 (Caputo and Viotti 1970), but never simultaneously to the He II 468.6 nm line. Thus the 1985-1990 phase was the hottest one so far observed in AG Car. We have also for the first time identified O II in the spectrum of AG Car (Fig. 2c), while the C II \( \lambda \lambda 723.1-723.6 \) nm doublet is present in the red spectrum; the stronger C II \( \lambda \lambda 657.8-8.3 \) nm doublet is probably hidden in the intense H\(\alpha\)-[N II] blend. These latter lines have been identified in the very high resolution CAT-CES observations of February 1984, during the fading phase of AG Car when the [N II] lines were absent (Bandiera et al. 1989). The C II \( \lambda 657.8 \) line was still visible in the June 1987 spectrum in the wings of the [N II] 658.4 nm line (Bandiera et al. 1989). The O and C ions were not identified in the earlier spectra of Caputo and Viotti (1970), but this could be at least partially attributed to the lower quality of their spectra.

The richness in nitrogen lines of the spectrum of AG Car has suggested previous workers to hypothesize a N overabundance in AG Car, in agreement with some theoretical expectations. On the other hand the complex structure of the atmospheric envelope of this star might largely enhance some spectral lines and depress others, so that a reliable abundance determination is impossible without a good knowledge of the wind structure (see for instance the case of the carbon abundance in \( \eta \) Car discussed by Viotti et al. 1989). However, as discussed in the following section, a large N/O overabundance has been firmly found in the circumstellar AG Car nebulosity.

Another important argument is the velocity field in the wind of AG Car. In particular we have found that the high excitation He II and [Fe III] emission lines appear broad, suggesting line formation in an expanding medium with a velocity of about 200 km s\(^{-1}\). A similar velocity broadening is measured for the [N II] lines in the 1987 spectrum taken with the ESO CAT-CES (Bandiera et al 1989). Indeed, a careful analysis of
the profile of the [N II] 658.4 nm line in our, lower resolution red spectra confirms that these lines are broader than the other intermediate excitation wind features.

Most of the permitted lines in the 1990 spectrum of AG Car have a P Cygni profile with an E-A velocity difference from ~150 to >200 km s$^{-1}$, comparable with the broadening velocity measured in the above discussed high excitation emission lines. Our resolution of about 120 km s$^{-1}$ does not allow us to look for systematic velocity difference between different lines. We can only argue that the terminal wind velocity in mid 1990 should equal to or larger than ~250 km s$^{-1}$.

It may be interesting to compare the radial velocities measured in different phases of AG Car. Caputo and Viotti (1970) found the mean E-A velocities to be about 100 km s$^{-1}$ and 160 km s$^{-1}$ for the H and He lines respectively. Wolf and Stahl (1982) described a 12 A mm$^{-1}$ blue spectrum of AG Car observed in December 1981 near its maximum visual luminosity. This spectrum is characterized by many Balmer and Fe II lines with a P Cygni profile. The absorption components have a minimum at about 100-110 km s$^{-1}$, and their wings extend to about 150 km s$^{-1}$. In an unpublished 12 A mm$^{-1}$ spectrum of AG Car obtained by Altamore and Viotti at the Coudé focus of the 1.52 m ESO telescope in February 1983, when the star was one magnitude below maximum, the P Cygni absorptions of the strongest Balmer and Fe II lines appear double, with minima at E-A=90-100 and ~180 km s$^{-1}$. The wings are slightly more extended than in 1981, up to about 180 km s$^{-1}$.

3.2. The emission line spectrum of the nebula

As discussed in Section 2, from each CCD frame we have extracted a set of 45 calibrated spectrograms which have been used to derive the line and continuum fluxes across the ring nebula and outside it. The continuum data will be discussed in the next section. As already said, the first inspection of the spectra extracted from the “nebular” frames has revealed that the nebular emissions are detectable still far outside the ring. This fact indicates that the ring nebula is embedded in a diffuse nebular region (or halo). The presence of this halo is confirmed by an unpublished CCD Hα image of AG Car kindly put at our disposal by A. Altamore. Both our spectroscopic observations and the Hα image show that the nebular emission decreases outwards, indicating that it is associated with the star, rather than with the general Carina arm H I emission.

We have measured the flux of the following lines: Hα, Hβ, Hγ, [N II], and [S II]. The nebular [O I] 630-637 nm emission could also be present, but the doublet is largely masked by the [O I] sky lines. For the CCD frames centered on the star the smaller exposure times prevented us to derive good line fluxes much outside the central star. Two blue frames (5′′ N and 10′′ S) appear not well exposed in spite of the fact that the exposure time was the same as for the other images. Although the Hγ/Hβ flux ratio is in perfect agreement with those of the other frames, they have not been used for this study. Some spectra of the nebula in the red region are shown in Figure 3. The central spectra of the frames centered 5′′ South and North present a large similarity with the stellar one, suggesting that the nebular spectrum is partially due to starlight scattered by dust grains. This point will be discussed in the following section.

The measurement of the line fluxes has been performed by integrating the line profile between fixed couples of wavelength points, and using the same regions for the continuum level measurement. The results are plotted in Figure 4 where we report the line fluxes measured across the nebula. In the inner positions (0′, 5′′ N and 5′′ S) two maxima are visible on the opposite sides of AG Car which correspond to the two sides of the ring nebula crossed by the slit. In the 10′′ N and 10′′ S frames the two maxima are blended into a single peak, as expected from the ring geometry. For the [S II] lines the central points have been omitted in the 0′ images, as these lines are absent in the stellar spectrum.

Figure 4 indicates that for all the lines the position and the relative intensity of the two peaks changes in a continuous way with the declination, showing that both the geometry
and the emission column density largely deviate from spherical symmetry. Note also that a large nebular emission is present inside the ring. The spatial distribution of the intensities does not seem to be correlated with the jet like structure discovered by Paresce and Nota (1989).

Information about the physical conditions across and outside the ring nebula can be derived from the emission line ratios which are plotted in Figure 5. Concerning the Balmer decrement (Fig. 5a) we have computed the Hγ/Hβ ratio for all the slit positions inside the ring nebula only, because the intensity of Hγ vanishes immediately outside the ring. By averaging all the ratios along the slit we obtained a mean value of 0.36±0.12(rms). When dereddened with $E_{B-V}=0.7$, this figure corresponds to 0.47 which is in agreement with the theoretical case B ($T_e=10000$ K, $n_e=100$ cm$^{-3}$) value. However, the ratio seems to be variable across the nebula, being equal to 0.33±0.05, in the central parts of the nebula, and to 0.40±0.11 in the rims. This fact could be related to a larger extinction inside the ring nebula, but needs to be confirmed by new higher S/N observations.

For the Hα/Hβ flux ratio only the frames 10″N and 5″S have been used. The ratio show a large scatter which is probably due to the fact that the lines are measured in different frames. Inside the ring nebula the average value is 5.73±0.3 in agreement with the value recently found by Pacheco et al. (1992). In the log(Hγ/Hβ) vs. log(Hα/Hβ) plane (Cox and Mathews 1969) the representative point of the AG Car nebula is placed near the reddening line for pure recombination.

The [S II]λ671.7/673.1 flux ratio can be used to estimate of the electron density. These lines, in spite of their weakness, are measurable till the end of the slit in all the nebular spectra and the plot of the line ratio for all the spectral regions but excluding the region near the star, is given in Figure 5b. The mean ratio inside the nebula and outside it, is 0.95±0.03 and 1.20±0.08, respectively. The corresponding electron density within the nebula (for $T_e=10000$ K) is $n_e=580±60$, slightly lower than the value derived by Mitra and Dufour (1990) and
by Pacheco et al. (1992). Outside the nebula a much lower density of $n_e=180\pm80$ is derived.

Figure 5c shows the ratio Hα/[S\textsc{ii}]λ671.7+673.1. In the plot the inside and outside regions of the nebula are clearly marked, with a mean value of the ratio changing from 12.8 to 3.5. The anomalous maximum of about 20, not included in the mean, corresponds to the region 5"N of AG Car where the nebular spectrum is partially stellar scattered light, with strong Hα emission, as discussed in the next section. Note also that except in the above case there is no large variation of the ratio within the nebula, in spite of the large variation of the emission line intensity. The transition from the inner to the outer region is rather sharp, and takes 8-10 arcsec.

The Hα/[N\textsc{ii}]λ654.8+658.4 flux ratio is shown in Figure 5d. The ratio is larger in the external regions (2.4±0.08) than inside the nebula (1.37±0.06, excluding the central higher points due to the scattered star light). The latter is slightly lower, but still within the errors, than the values given by Mitra and Dufour (1990) and Pacheco et al. (1992). It is interesting to compare the above derived ratios for the inner and outer regions with the typical values for different astrophysical objects, such as Planetary Nebulae, H\,\textsc{ii} regions and SNRs. For this purpose we have used the diagnostics of Sabbadin et al. (1977) who used the intensity ratios of Hα, [N\textsc{ii}], and [S\textsc{ii}] lines. We have found that in all the diagrams, 671.7/673.1 vs. $\log$(Hα/[N\textsc{ii}]), $\log$(Hα/[N\textsc{ii}]) vs. $\log$(Hα/[S\textsc{ii}]), and 671.7/673.1 vs. $\log$(Hα/[S\textsc{ii}]), the representative points of the ring nebula of AG Car, and of the halo lie well within the PN and H\,\textsc{ii} regions, respectively. This confirms that the conditions in the outer regions are similar to those of typical diffuse nebulae, while the ring nebula is physically similar to large PNs.

### 3.3. The dust scattered nebular continuum

From a visual inspection of the CCD spectroscopic frames it appears evident that a diffuse continuum emission is present in the regions close to centre of the ring nebula. The possibility should be considered that it could at least partially due to stellar light scattered inside the instrument. However, we have found this continuum also in those frames corresponding to observations with the slit not centered on the star. In addition, an inspection of the frames of standard stars has shown that no scattered light of similar strength and extension is present. This fact makes us confident that the continuum observed in AG Car actually is nebular emission. We have measured the continuum flux in two emission-line free regions centered at 470 and 640 nm. In order to enhance the S/N ratio, 10 successive raws have been added up, which corresponds to an integration over 1 and 2 nm for the blue and red region, respectively. Figure 6 shows the variation of the blue and red continuum across the nebula at the different slit positions. Except for a marked anomaly for the 5"N frame near the star, the overall picture is that of a rather smoothed emission within the nebula, without an indication of an enhanced emission near the rings, as seen in the emission line plots (Fig.4). This gives evidence of a diffuse continuum emission from the whole AG Car nebula. Previous broad-band images have failed to detect the nebula in the blue (A. Altamore, private communication), or have only revealed the presence of a few peculiar features in the visual (Paresce and Nota 1989), or in the red (Nota et al. 1992). We attribute this diffuse continuum emission to the presence of dust grains in the whole extension of the nebula, which scatter the light from the central star. We have also noted that the continuum emission sharply decreases near the outer borders of the nebula.

In addition to the diffuse emission, we have found that the red nebular continuum is particularly enhanced in two regions 5"N and 5"S of AG Car (figures 3 and 6), extending to a few arcsecs in right ascension from the central star, in agreement with Nota et al. (1992). The spectrum 5"N appears quite similar to that of the star, with very strong Hα and [N\textsc{ii}] emission and the Hα 667.8 nm line with a marked P Cygni profile. The interstellar 628 nm band is also clearly visible. It is evident that the spectrum is partially nebular, as strong [S\textsc{ii}] lines are present, and partially scattered starlight. This scattered light has to be attributed to the presence of an increased amount of dust grains near the star. It should be noted that this position is at the opposite part of the dusty jet found by Paresce and Nota (1989). Actually, also in the position of the jet we have found emission due to scattered starlight, but less intense than in the anti-jet direction.
4. Towards a model of AG Car

Our observations of AG Car were made at a deep photometric minimum of the star which, in the constant bolometric luminosity model of Viotti et al. (1984), should correspond to a minimum size of the effective photosphere, about 10 times smaller than during the visual luminosity maximum of 1981. The June 1990 spectrum of AG Car present a lot of intriguing features, which are difficult to explain within a simple framework. Of special interest is the presence of a broad He II 468.6 nm emission line with an intensity much larger than that previously measured in 1985 (Stahl 1986), and in December 1990 (Leitherer et al. 1992) after our observations, indicating that AG Car was in the hottest phase so far recorded, in agreement with its low visual luminosity. The He II line is probably formed in the innermost layers of the AG Car wind. Its width indicates that in these layers the expansion velocity is large and close to the maximum wind velocity as discussed below.

Most of the emission lines identified in the June 1990 spectrum belong to ions within a rather small range of ionization energy (24 to 35 eV), suggesting a high wind temperature with a rather small temperature gradient. All the intermediate ionization lines display a P Cygni profile with an absorption component blue shifted up to $>200 \text{ km s}^{-1}$, suggesting a terminal wind velocity in excess of this figure. In this regard, it should be noted that no P Cygni absorption component was displayed by the N II lines in the spectra taken earlier in the minimum phase (Stahl 1986). This fact seems to suggest an increased density of the stellar wind in June 1990, which can be associated with the beginning of the new brightening phase of the star which started a few days after our observations.

Another peculiarity of the stellar spectrum is the presence of [Fe III] lines with a flat topped, possibly double peaked profile, which is reminiscent of the profile of the [N II] lines in the high resolution 1987 spectrum of AG Car described by Bandiera et al. (1989).

AG Car is not unique in displaying broad high excitation forbidden lines. For instance Israelian and de Groot (1992) have recently found that in P Cyg the [N II] lines are broad with a velocity width of 160 km s$^{-1}$. Damineli Neto et al. (1993) showed that also in η Car the [N II] lines have a complex profile with a total width of about 400 km s$^{-1}$. Since [Fe II] and [N II] should both be formed in the less dense outer parts of the wind of AG Car, their profile clearly indicates that the wind is still expanding at a velocity much larger than 100 km s$^{-1}$, quite far from the stellar effective surface. On the other hand, much lower motions have been observed in the nebula a few arcseconds from AG Car (e.g. Smith 1991), which implies a slowing down of the wind quite close to the star.

A further problem concerns the chemical composition of the stellar wind and of the ring nebula. If AG Car is an evolved massive star, we should expect marked composition anomalies. As discussed above, a CO underabundance of the stellar wind could be accounted for the weakness of the P Cygni C II and O II lines with respect to those of N II, but other effects, such as the different ionization energies should be also taken into account for a more precise estimate. On the other side our spectroscopic study of the nebula confirms previous conclusions that the matter in the nebula is overabundant in nitrogen. The point is whether this overabundance is that of the central star, or it is at least partially the result of some physical processes in the nebula.

As discussed in section 3.3, dust signatures have been found in different parts of the circumstellar environment of AG Car, even in regions very close to the star. This has led us to conclude that even in present times dust is continuously condensing from AG Car’s wind. Since carbon and oxygen are among the main components of different types of condensate, their possible underabundance in the stellar wind is difficult to reconcile with the presence of dust in the nebula, unless different types of condensate are considered. In this regards, we should mention the absence of CO molecular emission in the near-IR spectrum of AG Car, while it was detected in the similar star HR Car (McGregor et al. 1988a). We also recall that dust is continuously condensing from the η Car’s wind, in spite of its possible carbon underabundance (Viotti et al. 1989). Another problem concerns the physical conditions, low temperature and especially high particle density, required for dust to condense. This point was discussed by Andriesse et al. (1978) for the case of η Car. In this star as well as in AG Car the dust condensation is probably favoured by the breaking of the outflowing wind into denser cloudlets. This process could be associated with the change of the expansion velocity discussed above. Actually, the “jet-like” structure discovered by Paresce and Nota (1989) and the evidence (that we have confirmed) of a high dust density in the “anti-jet” position points to the possibility of an axisymmetric enhancement of the dust concentration. The jet itself could be composed by many badly resolved cloudlets. Whatever the mechanism of dust condensation be, it would reduce the CO abundance of the ejected gas, and be at least partially responsible of the anomalous abundance of the ring nebula.

Another piece of the puzzle is the structure of the nebula. Our data show that the ring nebula is surrounded by a much less dense, apparently spherically symmetric H II region which can be considered a residual of the stellar wind (or halo) of a previous evolutionary phase of the star. Indeed, as discussed...
in section 3.2, the nitrogen abundance in this halo is probably normal. The measure of the expansion velocity of the halo is crucial to understand whether it was ejected by a red supergiant. Only an upper limit of about 100 km s\(^{-1}\) can be derived from our low resolution spectrograms.

The outer boundary of the ring appears very sharp, both from a morphological and a spectroscopic point of view, which might suggest the presence of a physical discontinuity, i.e. a shock front. In any case the transition from the phase when the outer halo and the inner ring were formed was a discontinuity in the star evolution.

5. Conclusions

Our observations have disclosed a number of important data on the AG Car environment, which are schematically illustrated in figure 7. From the He II profile we have argued that during the 1990 hot phase, the stellar wind reached its velocity maximum near the stellar surface, indicating the presence on an effective wind acceleration mechanism. Then, at a distance of \(10^{18}-10^{19}\) cm, the outflowing matter is breaking into a large number of cloudlets, with a larger cloud density in the jet and anti-jet directions. The unknown breaking process is probably also helping the process of dust condensation and growth.

Since dust grains seem to be present everywhere, in the ring nebula as well as inside it, the dust condensation should have worked for at least \(10^4\) yr. This could be partially responsible of the CNO anomaly in the nebula. On the other hand, in the absence of reliable wind models, it is at present impossible to relate the observed weakness of the C II and O II P Cygni lines in the stellar spectrum with a CO underabundance.

All these observational facts cannot be explained by any simple model of the AG Car nebula, including the presence of a close companion or of a magnetic field as for instance suggested by Nota et al. (1992). On the contrary, they point to a complex interaction of different velocities in the wind, associated with different evolutionary phases of the central object, similar to those studied by Pascoli (1992) for the planetary nebulae formation, or to those suggested by Wang and Mazzali (1992) for the "Napoleon hat" nebula surrounding SN1987A. These interactions can also be the reason of the velocity discontinuity between the wind and the inner nebula.

A last evolutionary consideration follows from the determination of the star distance. As mentioned above, the most recent evaluation of the AG Car distance seems to favour a value \(\approx 6\) kpc (Humphreys et al. 1989, Hoekzema et al. 1992). If this figure is true, the corresponding large absolute luminosity would imply, following the current models, an evolutionary track not reaching the RSG phase. However, the large reddening of AG Car (\(E_{B-V}\approx 0.7\)) could be partially attributed to an excess of local reddening, due to absorption from circumstellar dust in the nebula as well as in the extended halo. An extinction of \(A_V\approx 0.025-0.05\) due to the cool dust in the ring was derived from the KAO far-IR observations by McGregor et al. (1988b). Also the innermost dusty regions discussed in this paper should contribute to a local extinction. The quantitative evaluation of the contribution of the hotter circumstellar grains to the stellar colour excess would require a detailed study of the IR energy distribution of the star, which is dominated by the free-free emission from the stellar wind (e.g. Bensammar et al. 1981). If the AG Car distance is that of the Carina complex, as suggested by Viotti (1971), its absolute luminosity (and thus its mass) should be definitely lower than that of the other LBVs. In this case the star can have experienced an RSG phase and would be now in an evolutionary phase that has not been previously recognized.

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