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Spatially Resolved Spectroscopy of AG Carinae, and Direct Evidence for Stellar Evolution: The Central Star of NGC 2392

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Spatially Resolved Spectroscopy of AG Carinae, and
Direct Evidence for Stellar Evolution: The Central Star of NGC 2392
A Final Report
(NAS5-31838)

AG Carinae

I. Premise of the Research

This report discusses the results of a study of spatially resolved IUE spectra of the luminous blue variable (LBV) AG Car by Bruce Altner (ARC; PI) and Steven N. Shore (CSC/GHRS; Co-I). Recent coronagraphic imagery of AG Car has shown intriguing new detail in the circumstellar shell surrounding the central star, including the existence of a spiral jet-like structure extending from the star into the southwest lobe of the nebula. The size of the jet and the nebula are well-suited for spatially-resolved spectroscopy with IUE, and one major goal of this project was to study the circumstellar environment of AG Car by employing Altner's POLYSTAR routine to extract UV spectra at various positions in the shell from newly observed and archival data. A paper based on these results, to be submitted to the *Astrophysical Journal,* is currently in preparation.

II. Observations

New spectra of AG Car were obtained at several locations during the two alloted US1 shifts, in addition to shorter exposures of the central star. The full set of spatially resolved spectra of AG Car studied in this program are listed in Table 1, below.

III. Results

We show in Figure 1 cross-dispersion profiles of typical SWP and LWP spectra obtained at three different ring positions. It is clear from these that a careful spatial extraction is necessary in order to obtain quantitative information about the sources which contribute flux in each case. For this purpose, we have applied deconvolution methods and the POLYSTAR spectral extraction technique (Altner 1989, *IUE Newsletter,* **37**, 43) to these and other spectra listed in Table 1. A summary of our findings so far is given below.

- *The obserservations are all consistent with a broad continuum source that precisely matches the spectrum of the central star taken at about the same time.* The integrated luminosity of the circumstellar "ring nebula" is about 0.05 $L_{\star}$. The UV surface brightness ratio is $\sigma_{CS}/\sigma_{AGCar} \approx 4 \times 10^{-4}$. We see no compelling evidence of significant differences between the scattered and stellar spectra at any of the epochs represented in the data, suggesting that the shell must be within roughly 0.5 pc of the central star (indications are that there have been some changes in the stellar spectrum over longer timescales than one or two years).

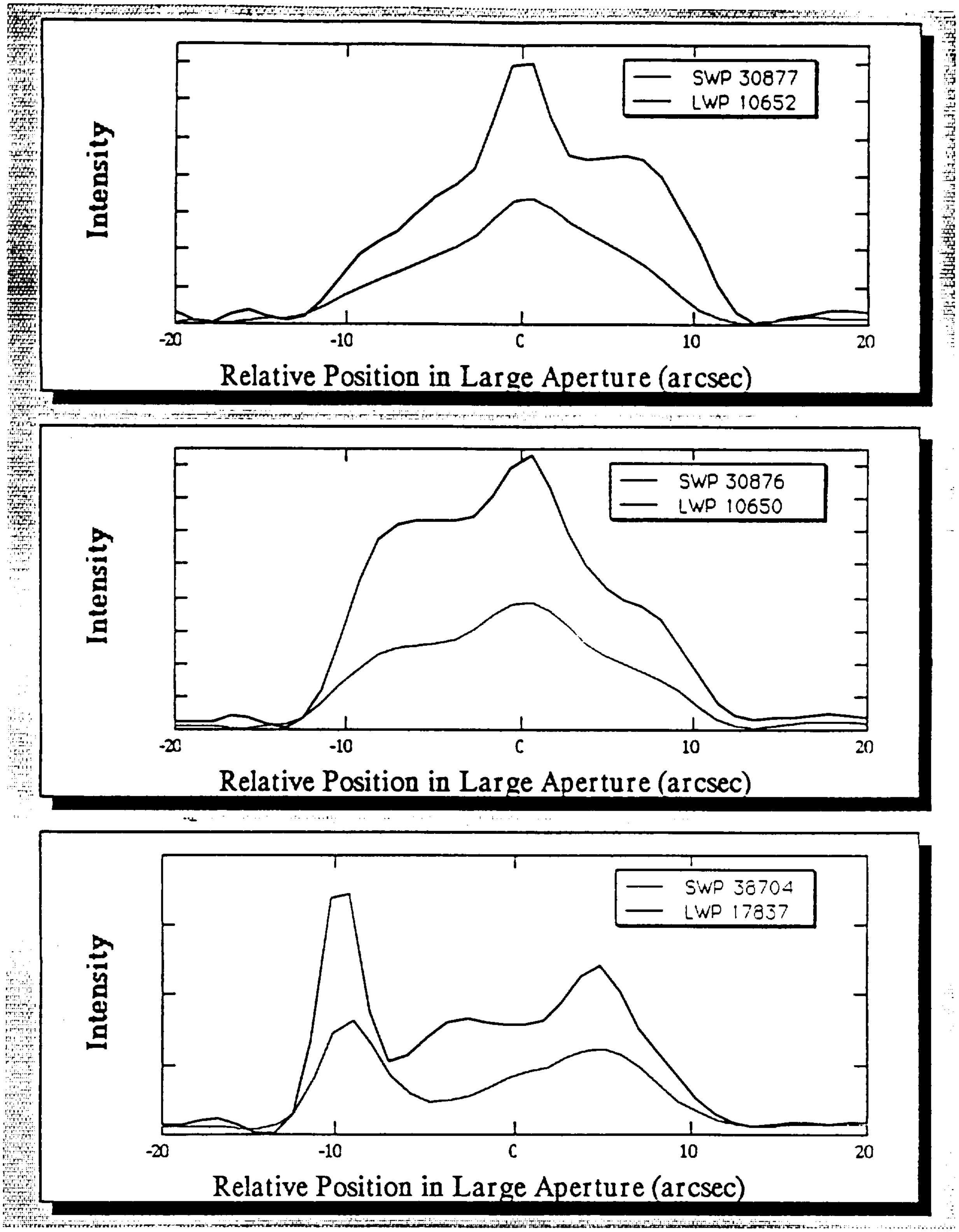

Figure 1: Spatial distribution of the UV signal in both the SWP and LWP apertures at three different pointings. The profiles have been deconvolved to remove the effect of the instrumental point spread function, and summed over the range 1250–1950 Å and 2400–3200 Å, for the short and long wavelength cameras, respectively. In all panels the SWP is the upper tracing, and the LWP is the lower tracing (original in color).

Table 1: **IUE Spatially Resolved Spectra of AG Car**

Pointing	CAM	Image	Exp(s)	YR	DAY	PA	α-off	δ-off	Observer(s)
NE	LWR	11314	7200	81	225	51	9.7	10.0	Viotti
CAR-A	SWP	14749	2400	81	225	51	-12.7	-13.0	Viotti
SW	LWP	10169	5700	87	53	243	-8.9	-10.0	Dufour and Mitra
SW	LWP	10650	7200	87	117	313	-7.1	-8.0	Mitra
NE	LWP	10652	7200	87	117	313	4.5	8.0	Mitra
NE	LWP	10657	18000	87	118	314	4.5	8.0	Mitra
SW	SWP	30355	7200	87	52	242	-9.7	-13.0	Dufour and Mitra
SW	SWP	30876	14400	87	117	313	-7.5	-8.0	Mitra
NE	SWP	30877	14280	87	117	313	4.5	8.0	Mitra
NW	SWP	30880	14400	87	118	314	-7.5	10.0	Mitra
NE	SWP	31413	25620	87	206	35	11.9	11.0	Cassatella
SW	LWP	17837	6900	90	120	317	-7.0	-7.5	Altner and Shore
SW	SWP	38704	7500	90	120	317	-7.0	-7.5	Altner and Shore
SW	LWP	17838	6900	90	120	317	-15.0	-1.5	Altner and Shore
SW	LWP	18540	6000	90	218	47	-9.8	-11.5	Altner and Shore

- *Dust scattering is the most likely interpretation of the origin of the UV continuum.* Observations at three key positions along the ring are all consistent with a uniformly mixed dust distribution at a distance of approximately 0.5 pc from the central star. The spectra derived from opposite sides of the ring do not differ substantially in continuum slope nor in the absorption line spectrum. However, an emission feature at λ1304Å (and possibly one at 1264Å) differs significantly between the northeastern and southwestern parts of the ring, being stronger on the southwestern side, in the vicinity of the dusty jet-like extension noted by Paresce and Nota (1989, *Ap. J. Letters,* **341,** L83).

- *There is strong evidence for a dust shell completely surrounding the central star, not just in the vicinity of the southwestern extension.* Noting that all of the pointings which cross the ring show the same level of continuum emission, it appears that dust scattering is observed throughout the same region from which the Hα emission arises. The resolution of the SWP slit-integrated spectra is poorer than in spectra of the central star. The broadened interstellar lines in these spectra are thus consistent with a filled aperture.

- *The evidence suggests that the grains are probably large.* This arises from the greyness of the UV scattering and also from the relatively warm temperatures ascribed to the dust by McGregor *et al.* (1988, *Ap. J.* **329,** 874). Here we outline the arguments supporting this conclusion:

    1. Employing the UV spectra, we can use observed quantities alone to estimate the grain temperatures. The UV heating is:

$$\Gamma_{UV} = \pi a^2 \int Q_\lambda^{abs}(a) F_\lambda^{IUE} \theta_{shell}^{-2} d\lambda \tag{1}$$

where a is the grain radius, Q is the efficiency, and θ_{shell} is the angular radius of the UV-detected shell. For the IR, we have the re-radiation efficiency:

$$\Lambda_{IR} = \pi a^2 \int \pi B_\lambda(T_g) Q_\lambda^{em}(a) d\lambda \tag{2}$$

where $B_\lambda(T_g)$ is the Planck function and T_g is the grain temperature. Approximating the emissivity using the Draine and Lee (1984, *Ap. J.*, **285,** 89) data for silicates (using $Q_\lambda^{em}(a) \approx a\lambda^{-2}$) gives $\Lambda_{IR} \sim T_g^6$. For silicates, we get $T_g =$ 43 K with no assumptions made about the stellar radius or distance, while we obtain a slightly higher temperature, 54 K, assuming 6 kpc. Assuming a grain size of 1μ yields $T_g \approx 30$ K. Large graphite grains give temperatures slightly higher, approximately 90 K. The quoted values are in close agreement with the results of McGregor *et al.* (1988) for the far IR grain properties of the shell. They had assumed a Kurucz (1979, *Ap. J. Suppl.*, **40,** 1) model with $T_{eff} = 25000K$ and $\log g = 3.0$ to be valid for AG Car, and our de-reddened UV continuum is a close match to this model, or the $\log g = 3.5$ case, using $E(B-V) = 0.67$.

2. The integrated IR shell flux is 1.4×10^{-8} erg cm^{-2}s^{-1} between 50 and 100μ (McGregor *et al.* 1988). The UV flux from the central star, corrected for reddening, is 7.2×10^{-7} erg cm^{-2} s^{-1}; thus about 2 percent of the stellar flux is re-processed in the circumstellar material. This is nearly identical to the result for several Galactic luminous blue variables, especially HR Car ($L_{IR}/L_{UV} \approx 0.01$) (Shore *et al.* 1990, *Ap. J.*, **73,** 461).

3. The UV surface brightness and integrated luminosity of the circumstellar material relative to the central star is of the same order of magnitude, about 5 percent, as the IR luminosity. The precise value is difficult to determine with the observations in hand because we do not sample the shell at a sufficient number of positions to be sure of the filling factor. However, from the extant observations we conclude that the scattering efficiency of the grains is of the order of their absorption efficiency (in other words, the albedo ≈ 1), and does not show significant angular dependence in the phase function. Both properties are consistent with large grains.

- From the UV brightness, using a shell thickness of order 3 arcsec (from the deconvolved, cross-shell slit orientations) and an approximate optical depth of order 0.05, we obtain $n_g \approx 7 \times 10^{-10} cm^{-3}$. This gives a dust mass of order $10^{-4.5\pm0.5}$M$_\odot$ for 0.1μ silicate grains. The IR images give $10^{-3.5} - 10^{-2}$M$_\odot$ (the assumptions are different from those used in the UV observations, in particular the size of the shell is assumed to be somewhat larger in the McGregor *et al.* paper than here). The optical data of Paresce and Nota (1989) are consistent with a shell mass of 10^{-3}M$_\odot$.

IV. Present and Future Work

We are currently working to improve the POLYSTAR extraction technique as part of an ADP-supported research project, (Altner and Shore 1992, *IUE Newsletter,* **48,** 148) and the AG Car study described herein and in the paper in preparation represents one of the programs which we believe will benefit from the improved procedure.

NGC 2392

I. Premise of the Research

This report describes the results of an IUE study by Sara R. Heap (PI; NASA/GSFC) and Bruce Altner (Co-I; ARC). The program was designed to search for signs of evolutionary changes in the central star of the planetary nebula NGC 2392, as evidenced by UV/optical fading over the lifetime of the IUE. This investigation was the precursor of a later study (14th and 15th IUE episodes) which included additional central stars over a wide range of spectral type (see final report for contract No. NAS5-31848). The results of this study, which found NGC 2392 to have a mass near 0.71 solar masses, have already appeared in the literature (Heap 1992, IAU Symposium 155, *Planetary Nebulae,* in press).

II. Observations

Four new low dispersion spectra of NGC 2392 were obtained in 1990. Together with two earlier spectra obtained in 1979, these data span an 11-year baseline, over which the central star was observed to fade at the rate of approximately 5% per decade (see Figure 1).

III. Data Reduction: UV Fading

In order to compare the IUE fluxes of a central star obtained over a more-than-ten-year timespan, several steps were necessary: 1) re-processing of observations prior to November 1981, to ensure uniformity of spectral image processing algorithms, 2) flux extraction, and 3) correction for the known rate of sensitivity degradation in the SWP camera. For the first step we used the SDPS system described in Feggans *et al.* (1988, in ESA SP-281, Vol. 2, p. 349) applied to the raw images. We verified that this yields almost the identical result as obtained by re-processing under IUESIPS, while being far more convenient for us to use. For the sensitivity correction we used a smoothed version of Garhart's (1992, *IUE Newsletter* **48,** p. 98) degradation curve, applied to the absolutely calibrated, merged-extracted low dispersion files. Finally, the spectra were binned, giving zero weight to flagged data points such as reseau and extrapolated-ITF pixels, in bandpasses which avoided nebular emission lines and P-Cygni features. In Figure 1 we show the results of the fading analysis (i.e., "light curves") for NGC 2392.

IV. Data Analysis: Stellar Masses

As first outlined by Paczynski (1971, *Acta Astr.,* **21,** 417), a central star of a planetary nebula evolves off the asymptotic giant branch to higher temperatures as its hydrogen-rich envelope is reduced – from the inside by nuclear burning, and from the outside by mass-loss in a stellar wind. The timescale for evolution is thus, $M_{env}/\dot{M}_{env}$. Because M_{env} is much smaller, and $\dot{M}$ is much larger in the more massive central stars, their timescale for evolution is drastically shorter. The evolution of the interior is manifested at the surface by UV/optical fading, and it is this which forms the basis of our conversion between fading rate and stellar mass.

We used the spectral energy distributions of the Kurucz 1991 models to estimate the initial brightness of a star of some initial T_{eff} in a given wavelength band. The observed optical-UV fading, caused by the diminishing brightness in that bandpass as the star evolves,

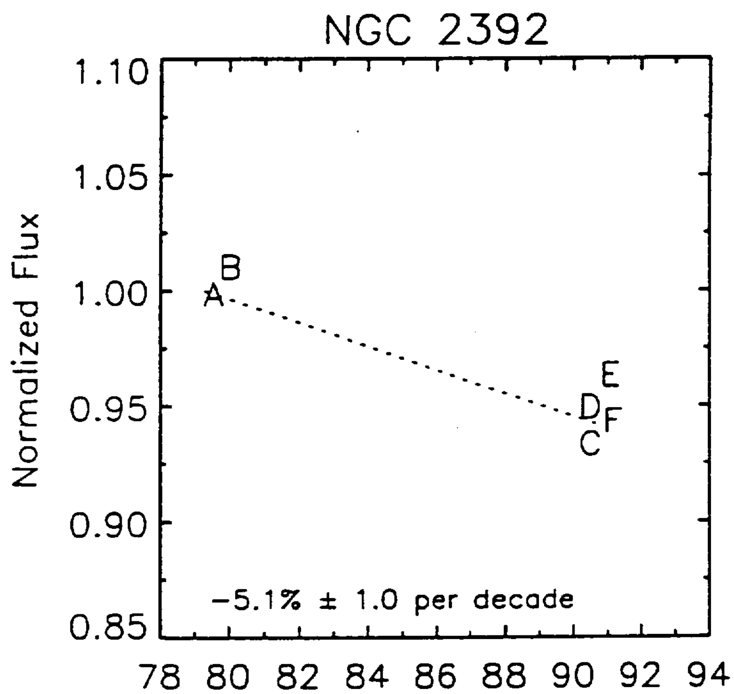

Figure 1: Fading of the central star of NGC 2392, based on IUE SWP spectra in the wavelength interval 1750 ± 50 Å. The slope of the least-squares fit straight line gives the fading rate, expressed as percent per decade.

thus leads to an estimate of the present, hotter temperature. We interpolated within the hydrogen and helium-burning evolutionary sequences of Blöcker and Schönberner (1990, *Astron. Astrophys.*, **240**), wherein the rate of change of temperature is given as a function of stellar mass, in order to transform the fading rates into stellar masses. The observed fading rate implies a mass of 0.71 solar masses for NGC 2392 (Heap 1992).

Future Work:

This program was extended in the 14th and 15th episode of IUE by the allocation of more observing time, which allowed us to obtain new SWP and LWP spectra of NGC 2392, as well as other central stars. The NGC 2392 spectra will serve as an important check that the trend observed in Figure 1 is maintained, thus strengthening the conclusion that the change is indeed due to the evolution of the star. Further analysis will include a re-evaluation of the estimated stellar mass using the most recent models of Blöcker and Schönberner (1992, private communication), as well as a thorough investigation of errors and uncertainties.

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16. Abstract

We have performed spatially-resolved low dispersion long-slit spectroscopy for the circumstellar shell of the luminous blue variable AG Carinae with *IUE* between $\lambda\lambda$ 1200 - 3200Å. At all positions a strong dust-scattered stellar continuum is detected. Only a few emission lines, Fe II 2600 and O I (?) 1304, have been detected; the emission is stronger on the southern side of the shell. The UV surface brightness and derived dust properties are completely consistent with the groundbased and KAO FIR observations: the grains are large (0.1 - 1μ), warm (45 - 100 K depending on composition), highly reflecting ($C_{sca}/C_{abs} \approx 1$), and tie up about 10^{-4} to $10^{-3}M_\odot$ of material. We also observe similarities of the results for HR Car and other LBVs to those reported here.

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