THE ASTROPHYSICAL JOURNAL, **268**:807–824, 1983 May 15

EPISODIC MASS LOSS AND NARROW LINES IN GAMMA CASSIOPEIAE AND IN OTHER EARLY-TYPE STARS[1]

H. F. HENRICHS AND G. HAMMERSCHLAG-HENSBERGE
Astronomical Institute, University of Amsterdam

AND

I. D. HOWARTH AND P. BARR
Department of Physics and Astronomy, University College London
Received 1982 July 22; accepted 1982 October 27

ABSTRACT

High-resolution ultraviolet spectra obtained with the *IUE* of the B0.5 IVe star γ Cas have revealed conspicuous changes in the profiles of the resonance doublet lines of C IV, N V, and Si IV. In 18 out of the 28 available spectra, narrow absorption components (FWHM ≤ 160 km s^{-1}) of varying strengths (up to almost saturated profiles) are found at the blueshifted side of the rest wavelength. Sometimes the components are multiple. In the range covered by the short-wavelength camera on board *IUE*, no other ions show such behavior. The central velocities of the narrow lines are between -650 and -1500 km s^{-1}. Within one spectrum the velocities of narrow lines in the three ions do not differ significantly. In the different episodes a larger column density is correlated with a lower velocity. For the development of such narrow high-velocity UV absorptions an upper limit of one week is derived from the data. The decay takes place typically within one month. The mean interval between the different episodes might vary between a week and a month. No periodicity has been found.

It is suggested that the occurrence of these narrow, high-velocity, high-excitation absorption lines (usually referred to as "narrow lines") might be a common phenomenon in all early-type stars, irrespective of luminosity class or Be characteristics. The main argument originates from a comparison of both occurrence and properties of the narrow lines in γ Cas with those in a sample of 26 OB stars analyzed by Lamers, Gathier, and Snow.

This comparison enables a determination of the (unobserved) terminal velocity of the stellar wind of γ Cas to be made and it was found to be at 1700 km s^{-1}.

The observations presented here are in agreement with a (phenomenological) model proposed earlier for the occurrence and properties of the narrow lines. It is suggested that these lines are formed in a rapidly expanding region of the stellar wind which has a higher density than the ambient "quiet" wind, and which has resulted from an enhanced mass flux of the star during a short time (about 1 day). For simplicity spherical symmetry is assumed. Both the observed time-dependent behavior of the strength of the narrow absorption lines and the observed distribution of the velocities can be explained by the model. Radiation pressure is suggested as the driving mechanism.

The physical cause of the proposed episodic mass-loss enhancement remains unexplained. The possibility that the occurrence of narrow components is associated with recently suggested instabilities in a radiation-driven stellar wind is discussed.

Subject headings: stars: Be — stars: early-type — stars: individual — stars: mass loss — ultraviolet: spectra

I. INTRODUCTION

The bright star Gamma Cassiopeiae (γ Cas) was the first known Be star (Secchi 1867). The star has spectral type B0.5 IVe (Lesh 1968) and is a rapid rotator ($v \sin i \approx 230$ km s^{-1}; Slettebak 1982). The star is surrounded by both emission and reflection nebulae (Poeckert and van den Bergh 1982). Its remarkable history in the visual region is well documented; the historical light curve has been given by Howarth (1979). Extensive reviews are given by Cowley and Marlborough (1968) and Cowley, Rogers, and Hutchings (1976). Since 1968 (Bohlin 1970) the star has also been extensively studied in the ultra-

[1]Based on observations by the *International Ultraviolet Explorer* collected at the Villafranca Satellite tracking station of the European Space Agency. Partly based on data retrieved from the ESA-*IUE* databank.

violet region by means of space instruments. Variability in UV lines in γ Cas was reported by Panek and Savage (1976). A recent description of the UV spectrum was given by Hammerschlag-Hensberge *et al.* (1980). A summary of the ground-based observations and earlier UV work is given by Snow, Peters, and Mathieu (1979). Infrared data are reviewed by Scargle *et al.* (1978). An upper limit for the radio flux has been given by Purton (1976) (see also Marlborough 1977).

New interest in γ Cas arose in 1976 when the star was discovered to be a low-luminosity X-ray source (MX 0053+604). For a review of all available X-ray data back to 1970 the reader is referred to Peters (1982*b*). The star appears to be a persistent, although variable, hard–X-ray emitter. The 0.5–60 keV luminosity of γ Cas is 5×10^{32} erg s^{-1} for a distance of 220 pc (Schmidt-Kaler 1964). A description of the X-ray spectrum is given by Peters (1982*b*) and White *et al.* (1982). In the latter paper a comparison of the X-ray properties of γ Cas with those of the X-ray binary system X Per/4U 0352+30 is made. Because of the great similarity between the two X-ray sources, the authors concluded that γ Cas is a member of a widely separated binary system containing an accreting neutron star, although no regular X-ray pulsations could be found. A similar binary model for γ Cas was also proposed by Marlborough, Snow, and Slettebak (1978). Radial-velocity studies of γ Cas have set limits to possible periodicity and amplitude (Cowley, Rogers, and Hutchings 1976), but no evidence for binary motion has been found.

Simultaneous UV and Hα studies have been presented by Slettebak and Snow (1978). They discovered short-time, simultaneous variability in these spectral regions, which also correlated with an X-ray flare.

Detailed models for γ Cas based on these and many other observations have been developed by Marlborough (1977), Poeckert and Marlborough (1977, 1978), Marlborough, Snow, and Slettebak (1978), and Scargle *et al.* (1978).

The unexpected presence of narrow, highly-displaced absorption components in ultraviolet resonance lines of C IV, N V, and Si IV was discovered by Hammerschlag-Hensberge (1979). This discovery motivated us to study γ Cas intensively with the *International Ultraviolet Explorer* (*IUE*).

The present paper gives extensive UV observations over a 2 year interval obtained with *IUE*. We give a detailed analysis of the transient, blueshifted, narrow, absorption components encountered in most of the available UV spectra. A short account of some of the data was given in an earlier report by Henrichs, Hammerschlag-Hensberge, and Lamers (1980, hereafter Paper I). In that paper a model for the occurrence of these transient features was proposed. It was suggested that the analysis of spectra taken with high time resolution (~ 1 day) should be able to test the model. Since then new observations with a time resolution of 2 days have been made and a preliminary report of these data has been given by Henrichs (1982, hereafter Paper II).

We interpret the narrow lines as due to a transient, variable, episodic (i.e., not periodic) enhanced mass loss from the star. These narrow-line features are tentatively identified as being a common phenomenon in all early-type stars. The arguments for this identification arise from a comparison of the properties of the narrow lines in γ Cas with those in a sample of 26 OB stars studied by Lamers, Gathier and Snow (1982, hereafter LGS). It is believed that the occurrence of the transient, narrow absorption features is fundamental for the understanding of the nature of mass loss in early-type stars. This idea was already expressed by Snow (1977).

The observational data are presented in § II. The analysis of the narrow absorptions is given in § III. Section IV summarizes the observed properties of the narrow lines in γ Cas. In § V arguments are given why γ Cas might be not unique as far as the occurrence of the narrow lines is concerned. Properties of the steady stellar wind of γ Cas are discussed in § VI. Models for the narrow lines in early-type stars are briefly reviewed in § VII. In the next section, the UV-shell model, which was proposed in Paper I, is extensively described and confronted with observations, both of γ Cas and of other early-type stars. A discussion of the model, suggestions for future research, and a discussion of the reported X-ray variability of γ Cas related to its possible binarity and to the UV-shell model are given in the last section.

II. HIGH-RESOLUTION *IUE* SPECTRA OF GAMMA CASSIOPEIAE

Table 1 presents the journal of the collected observations on γ Cas consisting of 28 high-resolution ultraviolet spectra obtained with the short-wavelength camera (1150–1900 Å) on board the *IUE* satellite. A description of the instrument was given by Boggess *et al.* (1978*a*, *b*). The spectral resolution is about 0.1–0.15 Å. The wavelength calibration was essentially derived from parameters provided by the observatory using onboard platinum lamps which produce reference spectra. In addition interstellar lines with known wavelengths are used to match the *IUE* spectral image with the wavelength-calibration image. The estimated absolute accuracy of the wavelength scale is better than 0.20 Å. No correction has been applied for the radial velocity of the star, which is about 4 km s^{-1} (Ferlet *et al.* 1980) corresponding to about 0.02 Å at 1500 Å.

Because of the diversity of the conditions under which the spectra were taken during the 2 year interval (such as quality of the instrument and reduction method), 21 of the spectra were reduced again, starting from the geometrically and photometrically corrected (GPHOT)

TABLE 1

LOG OF IUE HIGH-RESOLUTION SPECTRA OF GAMMA CASSIOPEIAE 1978–1980

Image SWP	Date	JD − 2,440,000	Narrow Lines?	Quality[a]
1321......	1978 Apr 6	3604.922	no	3
1449......	May 1	3629.604	no	2
1503......	May 7	3636.367	yes	2
2294......	Aug 14	3735.138	no	3
2385......	Aug 24	3744.943	no	1
2470......	Sep 4	3755.528	no	1
2681......	Sep 18	3770.056	no	*
2887......	Oct 8	3790.247	yes	1
4640......	1979 Mar 15	3947.809	yes	3
5928......	Jul 24	4079.126	yes	*
5929......	Jul 24	4079.144	yes	*
5959......	Jul 26	4081.210	yes?	*
6249......	Aug 22	4107.520	no	1
6268......	Aug 23	4109.394	no	1
6786......	Oct 7	4154.036	yes	*
6902......	Oct 18	4165.120	yes	1
6903......	Oct 18	4165.157	yes	2
6904......	Oct 18	4165.173	yes	2
7890......	1980 Feb 8	4277.533	no	*
8554......	Mar 25	4323.666	yes	2
8666......	Apr 5	4334.915	yes	2
8685......	Apr 7	4336.632	yes	2
8707......	Apr 9	4338.606	yes	2
8724......	Apr 11	4340.610	yes	2
8743......	Apr 13	4342.605	yes	2
9129......	May 26	4385.82	yes	2
9130......	May 26	4385.82	yes	2
9897......	Aug 25	4477.215	yes	*

[a] The agreement in flux of two adjacent orders is denoted by 1 when the agreement is excellent, 2 when acceptable, 3 when unreliable, * when not reduced in the present analysis.

image (2nd file). (The remaining seven spectra came to our disposal at a later time.) For images that were processed with the wrong Intensity Transfer Function (Holm 1979), we produced correct GPHOTs from the raw (1st file) image using a code provided by J. Settle (cf. Settle and Sanford 1980). The extraction was carried out at University College London with programs developed by J. Giddings (1981 and personal communication). These procedures give a more precise determination of the location of the spectral orders than can be expected from the standard reduction method. Another big advantage is that the resultant set of data is homogeneous with respect to the reduction. Background subtraction for high-dispersion spectra remains the most severe known inadequacy of the image-processing software, especially at the short-wavelength end of the image where the echelle orders are so close together that no true background can be located. Another problem is correction for echelle "ripple." Especially the long-wavelength edge of each order is affected by this error. In Table 1 the agreement in flux of two adjacent orders in the overlapping region is denoted in the last column. Uncertainty in the zero level will affect the results of the analysis only slightly. Because of the close distance of γ Cas (220 pc) there are not many saturated interstellar lines which would give an indication of the error in the background subtraction. We estimate the uncertainty in the zero level as being about 10% at the N V region and less at longer wavelengths.

The data points were finally mapped onto a uniform wavelength grid with an interval of 0.15 Å, using a triangular weighting function.

The spectra were rectified in three selected wavelength intervals (1170–1270 Å, 1320–1440 Å, and 1510–1590 Å) by means of a polynomial with four coefficients. In each wavelength interval the polynomial was fitted through all points within three to five selected wavelength regions of 2–20 Å width which were relatively free from absorptions. This method was chosen because it reduces random errors that are introduced by differences in the individual exposures. No attempt has been made to optimize the location of the continuum

1983ApJ...268..807H

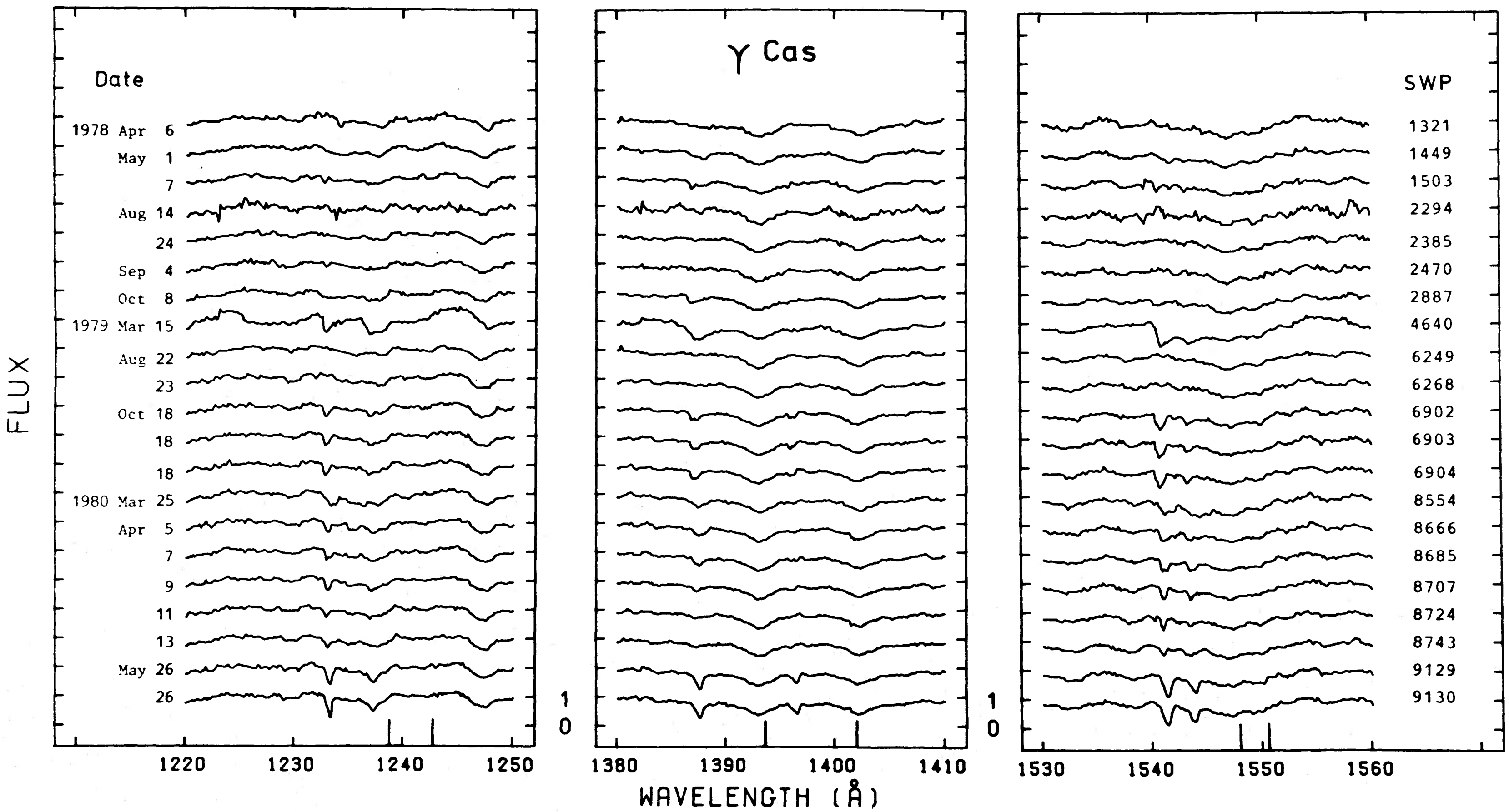

FIG. 1.—A selection of 21 spectra of γ Cas around the wavelength regions including the resonance doublets of N v (1238.8 and 1242.8 Å). Si IV (1393.8 and 1402.8 Å) and C IV (1548.2 and 1550.8 Å). The location of the laboratory wavelengths of the doublets are marked at the bottom line. Note the presence of variable absorption components displaced about 6 Å towards shorter wavelengths.

level, because it is of no importance in the analysis of the transient absorption features which we outline below.

Figure 1 contains 21 spectra that are reduced in this way in the three wavelength regions selected around the resonance doublets of C IV, N V, and Si IV. From this figure it is immediately evident that strong variations occur in the form of extra absorptions with typical velocities between -650 and -1500 km s^{-1} near the resonance lines. This variation was recognized for the first time in the spectrum of 1979 March 15 by Hammerschlag-Hensberge (1979).

III. ANALYSIS OF THE NARROW ABSORPTION LINES

Figure 2 illustrates the striking difference between a spectrum with and without the transient narrow absorption lines. There is some similarity between these narrow lines and interstellar lines; their origin, however, must be circumstellar because of the extremely high velocity and their transient nature.

Figures 3*a* and 3*b* show a superposition of the six spectra of the time series from 1980 March 25 to April 13, plotted on a velocity scale relative to the principal (short-wavelength) line of the resonance doublet for each of the three ions C^{3+}, N^{4+}, and Si^{3+}. It is obvious

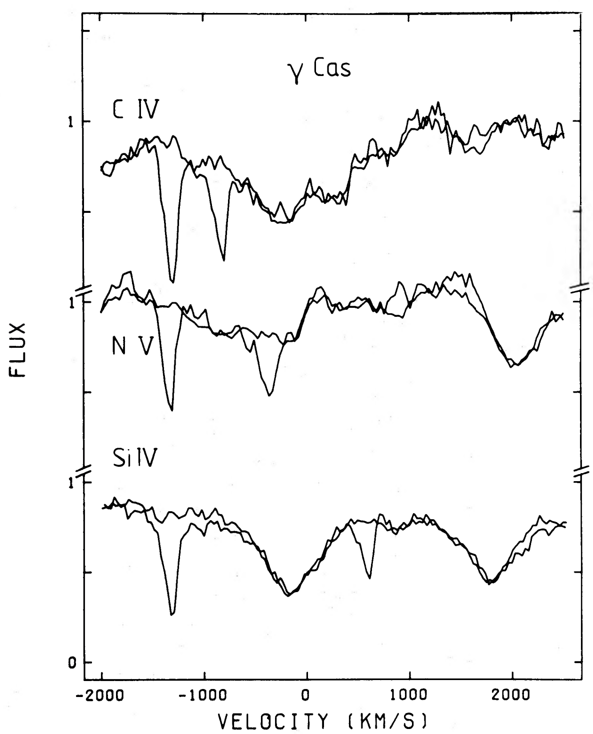

FIG. 2.—Example of a spectrum with (image 9129) and without (Fig. 4) the transient narrow absorption lines. The two spectra are superposed. In each row the velocity scale is relative to the rest wavelength of the principal doublet line of the ion. The narrow absorption lines are displaced by $\simeq -1300$ km/s.

from this figure that within the time span of 19 days large variations occurred simultaneously at the same velocity in each doublet. On some occasions the absorption features consist of multiple overlapping components. To disentangle the persistent absorption in the stellar spectrum from the transient absorptions we applied the following procedure.

First we constructed a mean spectrum consisting of four "clean" spectra containing no obvious indication of the narrow high-velocity lines and having acceptable quality (SWP 2385, 2470, 6249 and 6268). These spectra were taken on 1978 August 24 and September 4 and 1979 August 22 and 23, respectively. The mean spectrum was formed by taking the average value of the fluxes of the four rectified spectra at each wavelength grid point, after having verified that the interstellar lines were coincident. Three parts of the mean spectrum are shown in Figure 4. It should be emphasized, again, that no attempt has been made to draw the "best" continuum. The mean noise level in this spectrum is estimated to be less than 10% (3 σ).

The next step was to divide successively each spectrum by the mean spectrum. This was also accomplished after having verified that the interstellar lines coincided. The resultant spectrum is free from the persistent part of the stellar spectrum (including the interstellar lines) and the "continuum level" has the value unity at all wavelengths, except where the transient phenomena occur (this would not have been the case if we had subtracted the spectra). Because in the regions in which we are interested the mean spectrum does not have large flux changes across wavelength intervals that are comparable with a resolution element, the procedure followed does not suffer from effects due to the limited instrumental resolution.

In order to derive a column density for the narrow absorption lines in these "normalized" spectra we might have measured the equivalent widths. This method fails, however, when several overlapping doublets are present (notably in the first three spectra of the time series). We therefore derived the column density of each contributing doublet by a line fitting method. It was assumed that each doublet line pair is formed in a homogeneous plane-parallel slab of absorbing gas between the star and the observer. For a single line this gives the well known profile:

$$F(v) = \exp\left\{-\tau_0 \exp\left[-\left(\frac{v - v_c}{v_t}\right)^2\right]\right\}, \qquad (3.1)$$

where $F(v)$ is the "normalized" flux, i.e., unity outside the absorption part, v is the velocity, τ_0 is the optical depth in the center of the line which has a velocity v_c, and v_t is the broadening parameter in units of velocity. For a doublet we assumed that both components have the same value of v_t and that the central optical depths

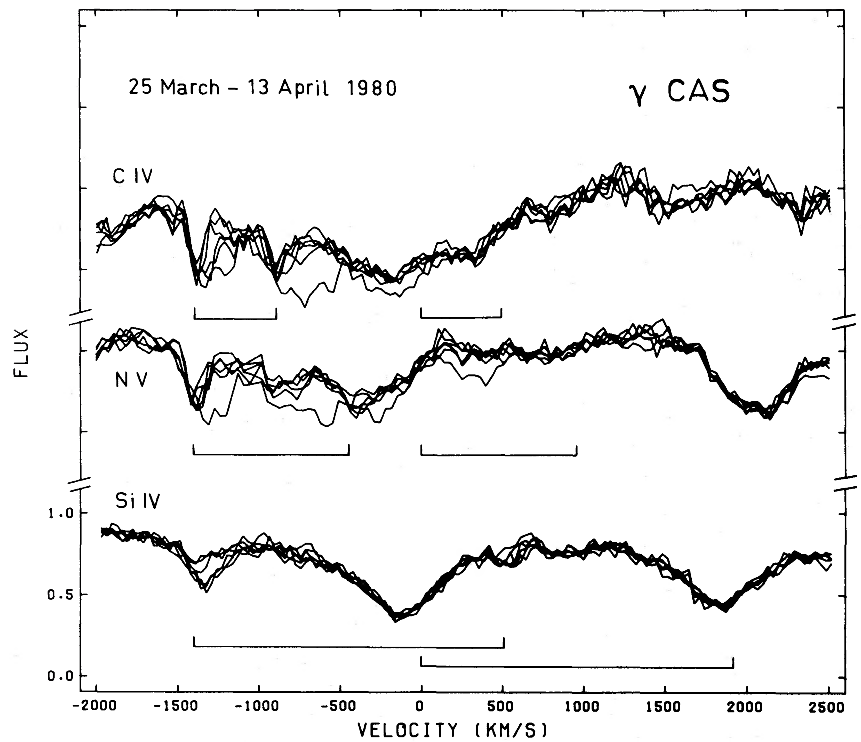

FIG. 3*a*.—Superposition of six spectra obtained between 1980 March 25 and April 13. In each row the velocity scale is relative to the rest wavelength of the principal doublet line. The undisplaced as well as displaced doublet splitting is indicated by horizontal lines.

and the Doppler shifted central velocities are related according to the expressions:

$$\frac{\tau_1}{\tau_2}=\frac{\lambda_1}{\lambda_2}\frac{f_1}{f_2}, \tag{3.2}$$

and

$$v_2=\frac{\lambda_2}{\lambda_1}v_1+\frac{\lambda_2-\lambda_1}{\lambda_1}c, \tag{3.3}$$

where the indices 1 and 2 apply to the principal and secondary line, respectively; λ is the laboratory wavelength; f the oscillator strength; and c the velocity of light. There are thus three free parameters (v_t, τ_0, and v_c) to be determined for each doublet. In the case of multiple, contaminated doublets, theoretical profiles of the type described by equation (3.1) can be combined, yielding a column density for each doublet.

The resultant theoretical profile is processed in three stages before a comparison with the spectrum is made. These stages consist of (1) a convolution with the instrumental profile, which is assumed to have a Gaussian shape with $\sigma=1.7$ pixels; (2) a simulation of the reduction programs described by Giddings (1981); and (3) a mapping onto a wavelength grid according to the method described in the previous section. The three fitted parameters are varied until the sum of the squares of the deviations between the calculated and observed spectrum is minimized.

The column density for any of the components follows from the relation:

$$N=\frac{\sqrt{\pi}}{\pi e^2/mc}\frac{1}{\lambda_0 f}\frac{\tau_0 v_t}{(1+v_c/c)}, \tag{3.4}$$

where $\pi e^2/mc$ has its usual meaning and λ_0 is the laboratory wavelength of the principal line. The atomic data were taken from Lamers and Morton (1976). We note that equation (3.4) (which implies eq. [3.2]) is valid for both optically thick and thin lines.

The values of the three parameters v_t, τ_0, and v_c and the column densities obtained in this way for each ion in all spectra with narrow absorptions are collected in Table 2. Figure 5 illustrates calculated and observed (normalized) spectra of profiles with several components.

IV. OBSERVED PROPERTIES OF THE NARROW LINES IN GAMMA CASSIOPEIAE

From Table 2 we derive the following conclusions:

1. Out of the 28 spectra of γ Cas collected in Table 1 we find on 18 occasions narrow, high-velocity absorp-

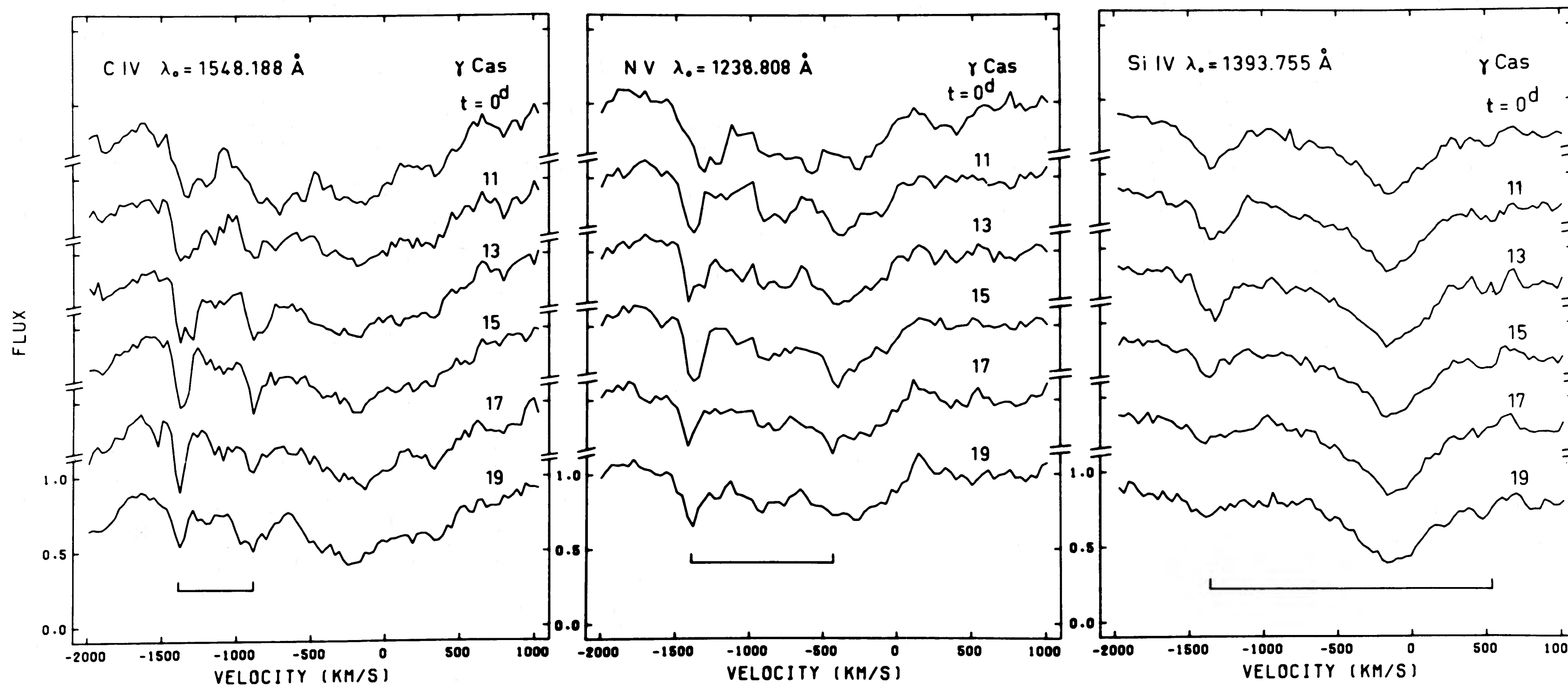

FIG. 3*b*.—The same spectra as in Fig. 3*a* are shown separately. In each panel the velocity scale is relative to the rest wavelength of the principal doublet line. A time axis is added (units in days, arbitrarily starting at $t = 0$ at the first spectrum). The location of narrow high-velocity absorption lines is indicated by marks. In the first three spectra of the time series several narrow components are present. The column density of the narrow lines clearly decreases as a function of time, while the central velocity hardly changes.

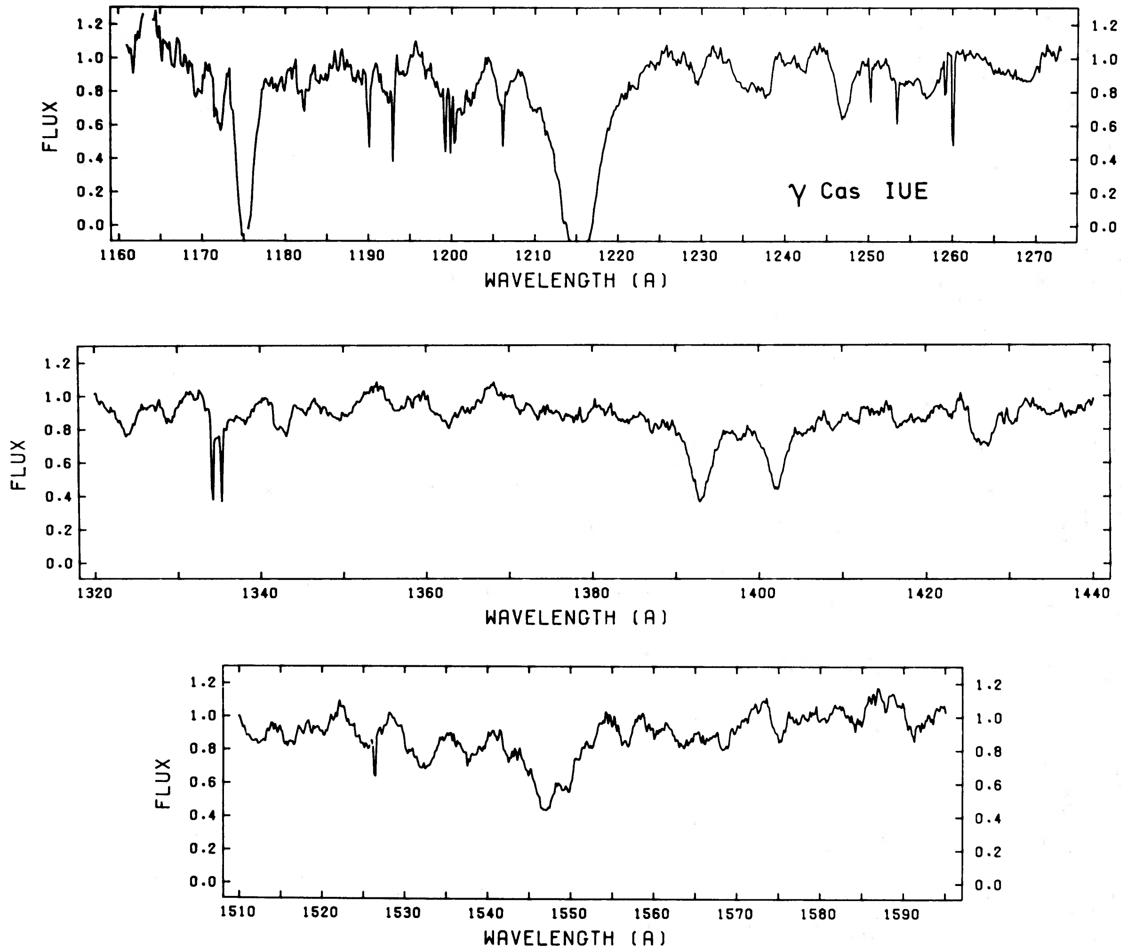

FIG. 4.—Rectified parts of the mean spectrum of γ Cas obtained by a combination of four spectra without narrow high-velocity lines. No attempt has been made to optimize the stellar continuum level. This spectrum served as a reference spectrum for the analysis of the narrow absorption lines (see text).

tion components in the resonance doublets of C IV, N V, and very often in Si IV. Only when the narrow absorptions in C IV and N V are weak are they not found in Si IV. In a few spectra two or three components with different velocities are present at the same time.

2. The central velocity of the narrow components relative to the rest frame of the star is usually between -1300 and -1500 km s^{-1}. On one occasion (1980 March 25) a strong component was found at -650 km s^{-1}. The uncertainty in the location of the line center relative to the adopted velocity scale is about 5–15 km s^{-1} (1 σ). The absolute uncertainty, however, is affected by the errors in the absolute wavelength scale. We estimate the total possible error, when comparing the velocities in the different ions, to be about 50 km s^{-1}. Within this error range the velocities of the narrow lines in the three ions do not differ significantly.

3. The central depth of the absorptions varies from only a few times the noise level to almost saturated (1980 August 25). In an optical depth scale the range is $\tau_0 \approx 0.15$–2.5.

4. The broadening parameter v_t (which is 0.60 times the full width at half-minimum), as derived from the analysis, varies between 50 and 100 km s^{-1} with an uncertainty ranging from 5 to 20 km s^{-1}. Usually the C IV components are a little broader than those of N V. The mean values of v_t for these ions are about 70 and 60 km s^{-1}, respectively. The Si IV lines are systematically broader, with a mean value of $v_t \approx 90$ km s^{-1}. One possible exception is found in the weakest set of lines (1978 May 7), where the Si IV line seems to have the smallest width.

5. There exists a clear correlation between the measured column density and the central velocity of the narrow lines. For all three ions a higher velocity corresponds to a smaller column density (see Fig. 6). For the series in 1980 March–April we took the mean value of the six column densities. We emphasize that this relation

1983ApJ...268..807H

TABLE 2

NARROW LINES IN GAMMA CASSIOPEIAE

SWP IMAGE	C IV v_t	C IV τ_0	C IV v_c	C IV N	N V v_t	N V τ_0	N V v_c	N V N	Si IV v_t	Si IV τ_0	Si IV v_c	Si IV N	NOTES
1321 ...	...	...	...	...	...	...	...	...	...	...	...	...	
1449 ...	...	...	...	...	...	...	...	...	...	...	...	...	
1503 ...	46	0.55	−1455	0.56	68	0.26	−1461	0.64	32	0.48	−1504	0.14	
	±11	±0.14	±8	±0.20	±16	±0.06	±11	±0.21	±15	±0.21	±9	±0.09	
2294 ...	...	...	...	...	...	...	...	...	...	...	...	...	
2385 ...	...	...	...	...	...	...	...	...	...	...	...	...	
2470 ...	...	...	...	...	...	...	...	...	...	...	...	...	
2681 ...	...	...	...	...	...	...	...	...	...	...	...	...	
2887 ...	144:	0.38	−1425	1.22:	87	0.23	−1459	0.70	57	0.36	−1507	0.18	1
	±12	±0.03	±9	±0.15	±19	±0.05	±14	±0.21	±14	±0.09	±10	0.06	
4640 ...	157:	1.30:	−1344	4.56:	139:	0.70:	−1379	3.47:	207:	0.55:	−1349	1.04:	2
	±9	±0.11	±8	±0.46	±15	±0.09	±11	±0.56	±17	±0.05	f	±0.12	
5928 ...	88	0.59	−1382	1.16	76	0.68	−1418	1.85	...	...	...	...	3
	±28	0.18	±18	±0.51	±17	±0.14	±14	0.57					
5929 ...	85	0.57	−1390	1.09	82	0.25	−1419	1.45	...	...	...	...	3
	±24	±0.14	f	±0.40	±19	±0.06	f	±0.49					
5959 ...	...	...	...	...	...	...	...	...	...	...	...	...	
6249 ...	...	...	...	...	...	...	...	...	...	...	...	...	
6268 ...	...	...	...	...	...	...	...	...	...	...	...	...	
6786 ...	85	0.69	−1399	1.30	99:	0.61:	−1400	2.15:	135:	0.41	−1395	0.58:	4
	±21	±0.19	±15	±0.48	±20	±0.12	±13	±0.62	±20	±0.10	±39	±0.16	
6902 ...	93	0.97	−1423	2.02	62	0.51	−1409	1.12	100	0.36	−1431	0.33	
	±11	±0.14	±8	±0.36	±11	±0.09	±7	±0.28	±14	±0.05	±10	±0.07	
6903 ...	72	0.84	−1408	1.35	65	0.46	−1405	1.07	92	0.38	−1431	0.32	
	±6	±0.09	±5	±0.18	±10	±0.07	±7	±0.24	±12	±0.05	±8	±0.06	
6904 ...	76	0.99	−1413	1.68	65	0.54	−1414	1.24	89	0.42	−1443	0.34	
	±6	±0.09	±4	±0.20	±10	±0.09	±7	±0.27	±12	±0.06	±9	±0.06	
7890 ...	...	...	...	...	...	...	...	...	...	...	...	...	
8554 ...	80	0.83	−1350	1.48	90	0.52	−1325	1.67	95	0.40	−1380	0.35	5
	±9	±0.08	±15	±0.20	±10	±0.05	±25	±0.25	±12	±0.05	±10	±0.06	
	75	0.63	−1214	1.05	70	0.35	−1180	0.87	70	0.14	−1215	0.89	
	±10	±0.06	±15	±0.18	±15	±0.04	±25	±0.21	f	±0.01	f	±0.09	
	198	0.51	−650	2.24	258	0.31	−590	2.84	150	0.10	−670	0.14	
	±16	±0.05	±40	±0.29	±20	±0.03	±15	±0.36	±50	±0.03	f	±0.06	
8666 ...	135	0.67	−1328	2.04	70	0.52	−1366	1.29	125	0.31	−1344	0.36	6
	±11	±0.06	±8	±0.24	±11	±0.09	±8	±0.30	±16	±0.04	±11	±0.06	
8685 ...	46	0.90	−1385	0.93	36	0.45	−1408	0.58	127	0.32	−1354	0.37	7
	±7	±0.15	±10	±0.21	±11	±0.13	±10	±0.25	±19	±0.05	±14	±0.08	
	52	0.73	−1295	0.84	46	0.34	−1302	0.55	...	...	...	...	
	±9	±0.12	±10	±0.20	±14	±0.09	±18	±0.23					
8707 ...	52	0.85	−1366	0.98	54	0.65	−1360	1.24	97	0.21	−1402	0.19	
	±5	±0.09	±3	±0.15	±7	±0.09	±5	±0.24	±18	±0.04	±13	±0.05	
8724 ...	65	0.66	−1379	0.96	58	0.38	−1390	0.78	...	...	...	...	8
	±9	±0.10	±6	±0.19	±8	±0.05	±5	±0.15					
8743 ...	50	0.73	−1386	0.81:	95	0.33	−1363	1.12:	...	...	...	...	9
	f	±0.12	±7	±0.14	±11	±0.04	±8	±0.18					
9129 ...	69	2.19	−1328	3.35	66	1.06	−1327	2.51	78	1.02	−1352	0.72	
	±4	±0.22	±3	±0.40	±7	±0.13	±5	±0.40	±6	±0.10	±4	±0.09	
9130 ...	68	2.20	−1328	3.33	49	1.54	−1319	2.70	83	1.02	−1349	0.78	
	±4	±0.23	±3	±0.40	±6	±0.28	±4	±0.59	±6	±0.10	±5	±0.09	
9897 ...	62	> 2.45:	−1320	> 3.37:	59	1.84	−1304	3.85	92	0.64	−1316	0.54	10
	±6	±0.48	±5	±0.74	±9	±0.48	±7	±1.16	±8	±0.15	±21	±0.14	

EXPLANATION OF SYMBOLS.—v_t is the turbulent velocity ($v_t = 0.60$ FWHM). Units are km s^{-1}. τ_0 is the optical depth at the line center of the principal line of the doublet. v_c is the velocity of the center of the principal line of the doublet relative to the laboratory wavelength of the line. Units are km s^{-1}. N is the column density. Units are 10^{14} cm^{-2}. : indicates uncertain value; see note. f means that this parameter was kept constant during the fit. ± All quoted errors are 1 σ formal errors.

NOTES.—(1) C IV line is heavily disturbed. (2) Unusually large ripple error. Values are very uncertain. (3) Spectrum is very noisy, probably due to small slot exposure. (4) N V line is very noisy. Si IV line is disturbed. (5) N V and Si IV regions are affected by ripple errors. Fig. 5 displays fit. (6) Lines are very broad, suggesting two unresolved lines. (7) Si IV line is broad and probably double. (8) Si IV region is noisy. (9) C IV and N V second lines are disturbed. Si IV region is noisy. (10) C IV principal line is saturated. Zero level is uncertain; hence quoted values are lower limits.

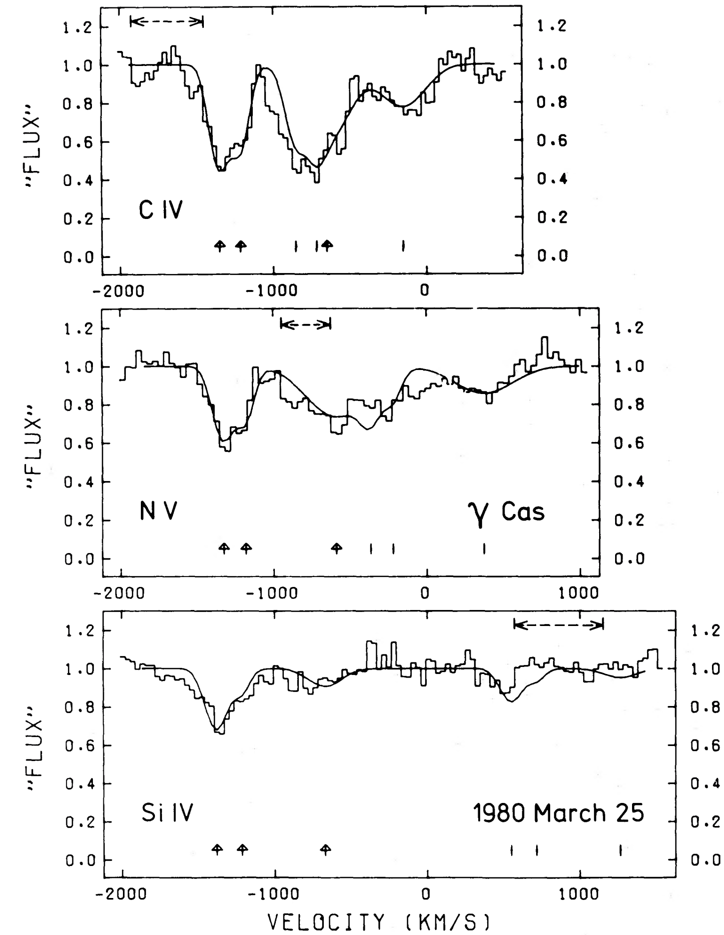

FIG. 5.—Calculated best fit profiles (obtained according to the method described in § III) with three components are drawn by a smooth line superposed on the "normalized" spectrum of 1980 March 25 for the narrow-line spectra of C IV, N V, and Si IV (see text for a description of the procedure followed). The positions of the two doublet lines are indicated by arrows and tick marks, respectively, at the bottom of the figure. At the top of each panel the regions are marked where adjacent echelle orders overlap (indicating a region with possibly larger uncertainty in the relative flux values). In the Si IV spectrum the component with the lowest (negative) velocity was arbitrarily added.

holds for the individual narrow-line episodes and that in the time series the velocity hardly changed.

6. The ratio of the ion column densities N(C IV)/N(N V) varies from 0.7 to 1.7 with a mean value of 1.2. The ratio N(C IV)/N(Si IV) is between 4 and 6.5 with a mean value of 5.1. There is no correlation of these ratios with the central velocity of the narrow lines, nor with corresponding ratios of the values of the broadening parameter.

7. The time scale between two spectra in which narrow lines are absent in the former and present in the latter, varies from $\leq 6^d$ to $\leq 46^d$. The time scale for disappearance is from less than ~ 4 weeks (1979 July–August) to less than ~ 16 weeks. Figure 7 displays the mean column density of the narrow lines in the C IV and N V doublets as a function of time. No periodicity in the presence of the narrow lines can be derived from the available data. An overall increase of the strength of the narrow lines in the different episodes is possible.

8. In the six spectra of the time series in 1980 March–April the column density is a strongly decreasing function of time (see Fig. 3*b* and Paper II).

V. ARE TRANSIENT NARROW ABSORPTION LINES A COMMON PROPERTY OF EARLY-TYPE STARS?

An obvious but very fundamental conclusion from our study is that the narrow absorption lines are *transient* phenomena. We found that in 18 out of 28 spectra of γ Cas the narrow lines are definitely present. We would therefore classify the occurrence of these lines as a rather common phenomenon in γ Cas. To our knowledge γ Cas is the only star for which such an extensive record of detailed observations of the narrow lines

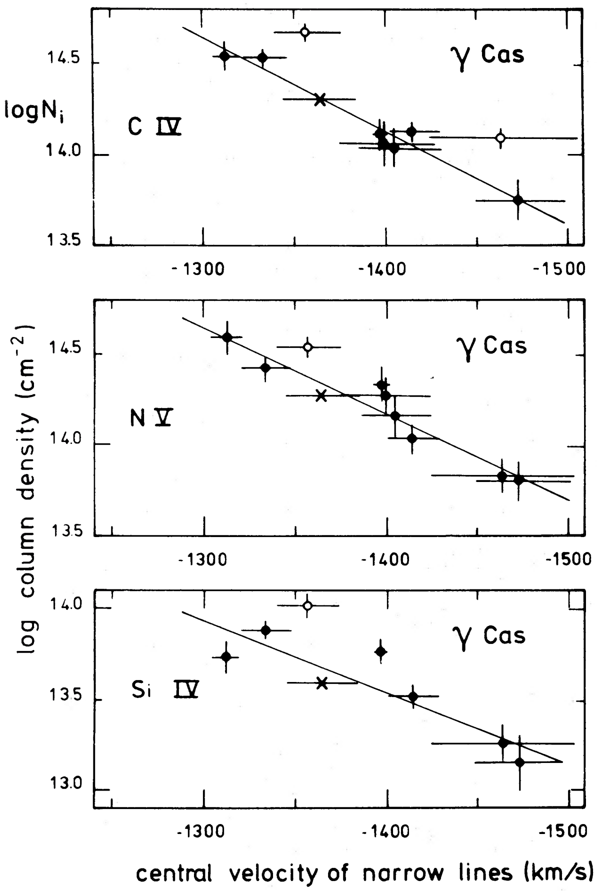

FIG. 6.—Relation between the measured column density in the different episodes and the corresponding central velocity of the narrow lines. The open circles denote uncertain measurements (notably the values of the spectrum of 1979 March 15, see Table 2 and Fig. 1). The crosses are the average values for the values of the time series in 1980 March–April. Error bars are 1 σ formal errors (see Table 2).

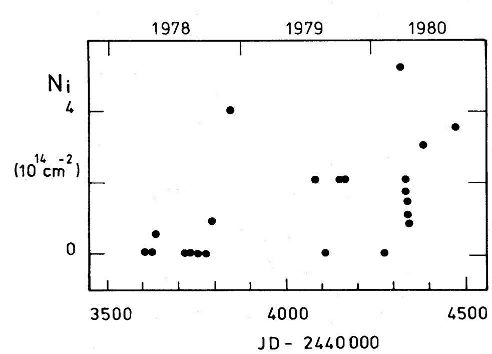

FIG. 7.—Mean column density N_i of the narrow doublet lines in C IV and N V as a function of time for γ Cas. No periodicity in the occurrence of the narrow lines can be derived from the data.

exists. A natural question is whether γ Cas is, in this respect, exceptional. If not, any model to explain the narrow lines in γ Cas must apply to other stars as well. Therefore it is very important to investigate the uniqueness of γ Cas, before discussing possible models. One might argue that γ Cas is well known to have a quite remarkable history, at least in the visual wavelength region, which would make it an exceptional object. However, the following arguments favor the opinion that the appearance of the narrow UV lines is typical not only for γ Cas, but possibly also for most other OB stars.

1. Although in the visual region γ Cas is classified as a Be star (because of its hydrogen emission), its present ultraviolet spectrum is not very different from that of a "normal" O or B star. In particular, when rotational broadening is taken into account, the strong resonance lines of ions like C^{3+}, N^{4+}, and Si^{3+} in which the narrow lines are found are very similar in both Be and B dwarf stars.

2. The transient absorption lines are encountered only in the resonance lines of highly ionized species, which are found in the ultraviolet region. One should compare this with the variability and/or occurrence of these narrow lines in spectra of other O and B stars. The first evidence for rapid (i.e., hourly) variations in the O VI P Cygni lines was found by York *et al.* (1977) in ζ Pup (O4 If), λ Ori A [O8 III((f))] and ι Ori (O9 III). A systematic search for variable UV lines in early-type stars was carried out with the *Copernicus* satellite by Snow (1977). Significant variability in C III, Si IV, and N V lines over a time base of 2–4 years was reported for several stars of spectral type O4 to B1 and luminosity class I to V (Be stars were not included in the sample). Snow stressed the occurrence and variability of the narrow absorption lines and emphasized the significance of the existence of the narrow features for the stellar wind phenomenon in OB stars. A summary of UV variability in early-type stars was given by Snow (1979). A survey, concentrating only on the occurrence of the narrow lines, was presented by LGS. These authors analyzed UV spectra of 26 OB stars obtained with the *Copernicus* satellite (Snow and Jenkins 1977) and found narrow absorptions very similar to those observed in γ Cas in 17 stars. In their study only one spectrum of each star was considered. New observations with *IUE* of several stars in the sample of LGS (viz. ζ Oph (O9.5 V), μ Nor (O9.7 Iab), ζ Pup (O4 If), λ Ori A [O8 III((f))], *IUE* data bank, unpublished) show significant differences in the structure of the narrow lines with respect to the profiles analyzed by LGS. Both properties, the occurrence in other early-type stars and the reported variability, are suggestive of a common interpretation for this phenomenon.

3. A strong argument in favor of the view that γ Cas is not unique with respect to the narrow absorption lines

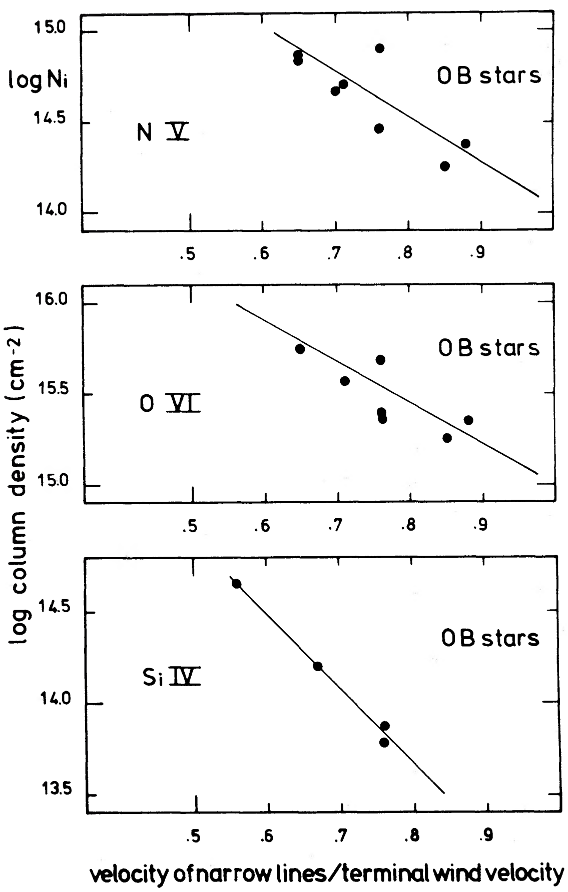

FIG. 8.—Relation between the column density and the ratio of the central velocity of the narrow lines to the terminal wind velocity for the ions N V, O VI, and Si IV in several OB stars (*Copernicus* spectra). The points are based on values obtained by LGS, where we omitted uncertain values (if so indicated by LGS). The sample contains O and B stars with luminosity classes in the range of I to V (no Be stars). The O VI doublet is outside the range of the *IUE* satellite.

comes from the statistics. In 18 out of the 28 available spectra of γ Cas these lines are present. This fraction is essentially the same as the fraction of stars with narrow lines in the sample of LGS, which is 17 out of 26. Their sample included O stars of all spectral classes from O4f to B1 Ib, except Be. Given the first two arguments presented above, this might be more than a mere coincidence.

4. In addition, the average value of the observed column densities for the narrow lines in the N V and Si IV doublets of γ Cas are in the same range as those found for the OB stars in the sample of LGS.

5. Moreover, the correlation between the column density and velocity found for γ Cas in the present paper appears also to be, surprisingly, present in the sample studied by LGS. This correlation is not mentioned in that paper but is essentially the same as in γ Cas if the column densities for the N V, O VI, and Si IV lines are compared with the central velocity relative to the terminal velocity (if observed) of the wind (see Fig. 8).

6. Another argument is found in the occurrence and variability of the narrow lines in other Be stars, although as a class this type of star is not well documented in respect of these lines. The best example is 59 Cyg (B1.5 Ve) (Doazan, Kuhi, and Thomas 1980; Doazan *et al.* 1980, 1982). For ω Ori (B3 IIIe) and 66 Oph (B2 Ve) variable and sometimes multiple absorption components have been reported by Peters (1982*a*). Also, ζ Oph (O9.5 Ve) exhibits large variability in the narrow lines (A. J. Willis 1982, private communication). There seems to be no correlation of the occurrence and/or velocity of the narrow lines with the rotational velocity of the star (Peters 1982*a*).

Based on these arguments we suggest the possibility that the narrow, high-velocity, high-excitation lines are transient phenomena, characteristic of all early-type stars, irrespective of spectral class or Be characteristics. We notice that this point of view was already expressed, but not further elaborated, in Papers I and II.

From the other side, there might also be differences between the properties of the narrow lines in γ Cas and those which are observed in some other stars, e.g., δ Ori A (O9.5 III), ι Ori (O9 III), 15 Mon [O7 V((f))] (Grady, Snow, and Cash 1982). From the (limited) amount of available data it might be concluded that at least in some stars the central velocity of the narrow lines is remarkably constant. In addition, the time scales involved might not be as short as those observed in γ Cas. Another contrast might be that in some stars the broad underlying P Cygni profile can change significantly, a change which has not been observed in γ Cas.

It is clear that detailed observations taken with a sufficient amount of time can resolve whether there indeed exist fundamental differences in the properties of narrow lines among early-type stars. The arguments presented above, however, seem to point toward a common origin of this phenomenon.

VI. MASS LOSS AND THE TERMINAL VELOCITY OF THE WIND IN GAMMA CASSIOPEIAE

In γ Cas the persistent parts of the resonance lines of C IV, N V, and Si IV resemble a P Cygni profile of type VI (Beals 1951), i.e., asymmetric toward the short-wavelength side and without appreciable emission. The asymmetry is produced by the outflowing matter. We notice that in our spectra the largest absorption occurs at about -200 km s^{-1} in all three ions. This is significantly different from the value of -100 km s^{-1} found in 1974 *Copernicus* spectra of γ Cas (Snow 1981). This might indicate a gradual increase in the steady mass-loss rate of the star. In Paper I (see also Hammerschlag-Hensberge *et al.* 1980) we derived a mass-loss rate $\dot{M} \approx 1 \times 10^{-8} M_{\odot}$ yr^{-1} for γ Cas. This value will be accepted in the present paper.

An important question is whether the velocity of the narrow lines in γ Cas is below the terminal velocity of the (steady) stellar wind, as are those observed in other early-type stars. We find that the blue side of the profiles joins the continuum at about 900 km s^{-1}. This velocity cannot be considered as the terminal velocity of the stellar wind of γ Cas because the persistent P Cygni lines are far from saturated. Therefore, a first estimate for the terminal wind velocity is based on the empirical relation found by Abbott (1978) according to which the terminal velocity is about 3 times the escape velocity (corrected for radiation pressure due to electron scattering) at the surface of the star, which is about 800 km s^{-1}, yielding a terminal velocity of $v_\infty = 2400$ km s^{-1}. We adopted 17 $M_\odot$ for the mass and 10 $R_\odot$ for the radius (Poeckert and Marborough 1978). The actual value of the terminal velocity might not be as high as the estimate given above because the rapid rotation of the star ($v_{eq} \sin i \approx 230$ km s^{-1} [Slettebak 1982], where v_{eq} is the rotational velocity of the star at the equator) tends to lower the escape velocity. Moreover, Lamers (1981) found that for stars cooler than about $T_{eff} = 30{,}000$ K, the ratio v_∞/v_{esc} is smaller than 3 and depends on the effective temperature. Adopting for γ Cas $T_{eff} = 25{,}000$ K (Poeckert and Marlborough 1978), we find $v_\infty \approx 2000$ km s^{-1}, which is greater than the highest velocity observed for the narrow lines in γ Cas.

Another estimate for the terminal velocity of the stellar wind in γ Cas can be made by an application of the relation found between the column density and the central velocity of the narrow lines in γ Cas (Fig. 6) and, on the other hand, the relation between the column density and the ratio v_c/v_∞ in the 26 OB stars studied by LGS (Fig. 8). In γ Cas the average values of the N V and Si IV column densities in the different episodes are $\log N(\text{N V}) \approx 14.3$ and $\log N(\text{Si IV}) \approx 13.7$, where we omitted the lowest values because these are below the detection limit in the LGS sample. The average central velocity is 1360 km s^{-1}. When we use the relation displayed in Figure 8 we find $v_c/v_\infty = 0.80$–0.85 for the N V doublet and $v_c/v_\infty \approx 0.78$ for the Si IV doublet. This yields $v_\infty \approx 1700$ km s^{-1} for the statistically most likely value for the terminal velocity of the stellar wind in γ Cas. This value agrees well with the estimate given above and is also greater than the greatest value observed for the narrow lines in γ Cas. Of course, this estimate is only justified if indeed the relations found (Figs. 6 and 8) are indeed based on the same physical origin.

We conclude that the central velocity of the narrow lines is in all cases below the terminal velocity of the wind.

VII. POSSIBLE MODELS FOR THE ORIGIN OF TRANSIENT NARROW ABSORPTION LINES

In a spectral line indicating mass loss there are in principle two different ways to explain an unexpectedly high column density at a specific velocity (relative to the rest frame of the star) that is lower than the terminal velocity of the stellar wind. Either there exists a velocity plateau at that particular velocity in the stellar wind, which increases the path length of the absorbing ions at the velocity of the plateau, or there exists a larger density of ions with that particular velocity.

Arguments against a stationary velocity plateau at intermediate velocities (below the terminal velocity of the stellar wind) as the explanation of narrow lines are given by LGS. In view of the multiple structure sometimes found and the transient nature of the narrow lines, we find it difficult to explain the strongly time-dependent column densities as due to one or more variable velocity plateaus.

A larger density at some specific velocity might be due either to ionization effects or to an enhancement of the total density, or both. The effect of the ionization structure on the observed P Cygni profile is clearly demonstrated by Drechsel and Rahe (1982). In their paper they show that P Cygni profiles, including narrow lines at high velocity very similar to those observed, are easily obtained by choosing a particular ionization structure. Similar profiles for a density structure in the form of a uniform expanding dense shell have been calculated by Rottenberg (1952).

A specific radial ionization structure produced by a temperature distribution that favors the occurrence of the relevant ionization stage at both low and high, but not intermediate, velocities (Doazan *et al.* 1980) is very unlikely when multiple components are found, unless one makes the (ad hoc) assumption that for every narrow component there exists another rise or fall in the temperature. The absence of any correlation between the velocity and ionization potential (in all spectra the three ions show the same velocities) also argues against such an explanation. The model of Doazan *et al.* (1980) is intrinsically unable to describe any time-dependent behavior, because in this model the mass flux is an independent stellar parameter (see also Doazan 1982). We note that this is also the case in the model elaborated in the present paper, but, in contrast, we propose that successive expansion of the matter is responsible for the behavior of the narrow lines (see below).

We now describe how a variable density, due to a variable mass-loss rate of the star, may explain in a natural way the observed characteristics.

VIII. EPISODIC MASS LOSS

We envisage that the star ejects a stellar wind that is steady (within a factor of 2) most of the time. Close to the star the velocity of the stellar wind increases very rapidly outward, i.e., within a few stellar radii the velocity almost reaches its terminal velocity (Fig. 9*a*). This rapid rise of velocity is a typical property of theoretically derived velocity laws, (e.g., for stellar winds driven by radiation pressure; Lucy and Solomon 1970 and

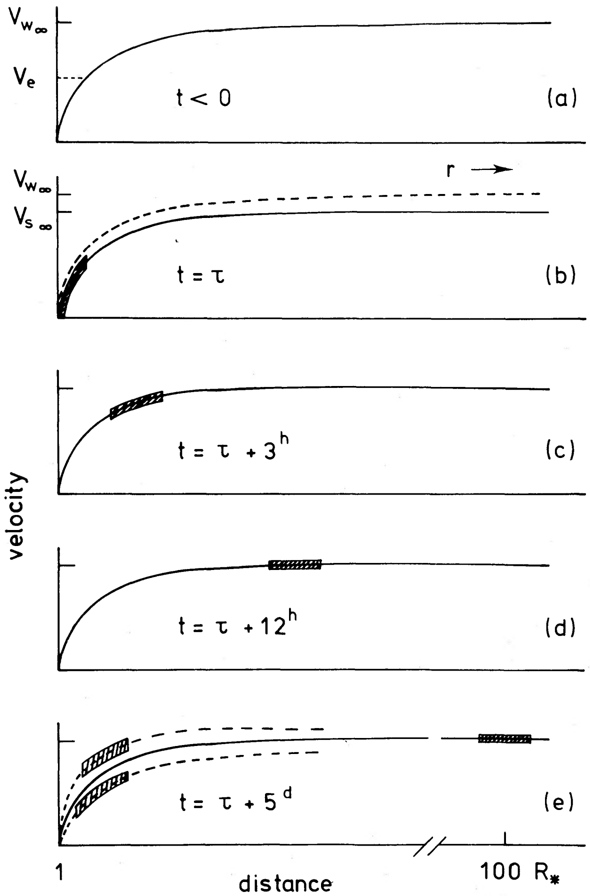

FIG. 9.—Symbolic representation of the velocity law for the steady wind and ejected "UV-shells" as a function of time according to the model described in the text. Fig. 9*a* shows a possible velocity law for the steady stellar wind. Note that the observed edge velocity v_e might have a lower value than the terminal velocity of the wind $v_{w\infty}$. Fig. 9*b* displays a possible velocity law followed by the ejected shell shortly after its formation. Because the density in the shell is higher than that of the steady wind, the terminal velocity in this new velocity law is lower. The velocity law of the steady wind of Fig. 9*a* is indicated by a dashed line. Figs. 9*c*, 9*d*, and 9*e* follow the shell after its formation. Notice the short time needed to reach the terminal velocity (a few hours). The travel time is about 20 R_* per day if we adopt a typical value of 17 $M_\odot$ for the mass and 10 $R_\odot$ for the radius of the early-type star. Fig. 9*e* shows the possible ejection of another shell (with a different velocity law) while the former shell is still present.

Castor, Abbott, and Klein 1975) as well as for emperically determined velocity laws (e.g., Barlow and Cohen 1977; Castor and Lamers 1979; Hamann 1980). This more or less steady mass loss is responsible for the persistent part of the P Cygni profiles. If the abundance of ions that produce the P Cygni lines is sufficiently high, the line profiles will be saturated and the terminal velocity of the wind $v_{w\infty}$ is observed at the steep edge of the absorption part at the short-wavelength side. If the lines are not saturated (in the case of γ Cas) the absorption part only extends to the edge velocity, $v_e < v_{w\infty}$.

a) *The UV-Shell Model*

In Paper I it was suggested that during a short time interval τ (typically on the order of 1 day) the mass-loss rate is strongly increased by a factor p:

$$\dot{M}_s = p\dot{M}_0, \qquad p \geq 2, \tag{8.1}$$

where $\dot{M}_s$ denotes the mass-loss rate during the ejection of the "shell" and $\dot{M}_0$ is the "steady" mass-loss rate (see Fig. 9*b* for a schematic representation). Both τ and p may differ in each episode. The time duration τ of the increased mass flux with enhancement factor p are not specified by the model. Successive expansion of the ejected matter will determine the behavior of the accompanying absorption. In Papers I and II this model was referred to as the UV-shell model because the presence of these "shells" is only noticed in lines that show mass loss, which are situated in the UV region of the spectrum. This model explains basically all the observed properties of the narrow lines.

b) *Physical Properties of the Shell*

We assume spherical symmetry, because deviations from spherical symmetry cannot be quantitatively accounted for because of lack of information. The driving mechanism for the ejected shell is presumably the same as for the steady wind (we assume radiation pressure), but the terminal velocity of the shell $v_{s\infty}$ might be different from $v_{w\infty}$ because of the higher density of the shell with respect to the "quiet" wind (Fig. 9*b*). How $v_{s\infty}$ and $v_{w\infty}$ are related depends on the exact mechanism of the driving force. If the wind and the shell are driven by radiation pressure it is expected that $v_{s\infty}/v_{w\infty} \approx \rho_w/\rho_\infty \approx p^{-1}$ in the extreme case that all driving lines (most of which are thought to be located in the unobservable far-UV) are completely saturated and nonoverlapping, i.e., that there are enough photons from the star to reach any ion that is capable of absorbing their momentum. In the other extreme case that all of the driving lines are optically thin, it is expected that $v_{s\infty} = v_{w\infty}$. In the radiation-pressure model, the observed relation $v_{s\infty} \approx (0.6\text{–}0.9)\ v_{w\infty}$ points toward an intermediate case in which some of the driving lines are saturated and some are not.

The velocity law for the shell will accordingly be different from that of the steady wind (Fig. 9*b*). In the present model the only (reasonable) requirement for the new velocity law is its typical rapid rise of velocity close to the star. The exact form of the velocity law is not relevant but might be inferred from the observations. We estimate a typical flow velocity for the shell to be about 20 R_* per day, where we adopted $v_{s\infty} \approx 1500$

km s^{-1} and $R_* = 10\ R_\odot$. This asymptotic velocity will be reached within a few hours (Figs. 9*c* and 9*d*). How long such a shell will be visible depends on its thickness (which is proportional to the formation time τ) and its density (which is proportional to the mass-loss enhancement factor p).

When the formation of a shell starts at time $t = 0$, ends at $t = \tau$, and the shell is observed at $t \gg \tau$, the rapid expansion of the presumably spherical shell will produce an absorption profile that resembles in a good approximation that of a plane-parallel slab of plasma (eq. [3.1]). We notice that in a spherically symmetric configuration the emission part of the profile is expected to be negligible. When pure resonance scattering is adopted as the absorption process, energy conservation demands that the equivalent width of the absorption equals that of the emission. The central velocity v_c of the narrow (i.e., $v_t \ll v_c$) absorption line will be the flow velocity of the shell. The emission part, however, will extend roughly from $-v_c$ to $+v_c$ and hence will be hardly noticeable. Unfortunately, the absence of emission gives no clue whether indeed the configuration is spherically, clumpy, or something else.

Several processes may contribute to the broadening parameter v_t. We mention geometric effects due to the curvature of the shell, thermal and turbulent broadening, differential rotation within the shell, and a velocity, density, and/or temperature gradient in the absorbing layer. Most of these effects may produce an asymmetric profile, which deviates from the assumed Gaussian shape of the optical depth across the line. Their relative importance might be derived from detailed observations of one particular shell episode.

The thickness of a shell will increase on a time scale which is roughly determined by the sound speed crossing time of the shell. At a typical temperature of 10^4–10^5 K (indicated by the presence of C IV, N V, and Si IV lines), the sound speed is about 40 km s^{-1}, or 0.5 R_* per day for a star with radius of 10 $R_\odot$. Because the sound speed crossing time is much shorter than the flow time, the shell is stable against dissipation. Hence the lifetime of a shell, or how long a shell can be observed, depends on the time scale for the decrease in column density. The formation time τ of the shell is short with respect to the lifetime of the shell. This allows the existence of multiple absorption components.

c) *Observable Properties of a UV-Shell*

We assumed that very soon the shell will have reached its terminal velocity. A spherically expanding shell will then give rise to a column density (in units of hydrogen atoms cm^{-2}) of

$$N_{\rm H} = \frac{X}{m_{\rm H}} A_E \frac{n_i}{n_{\rm E}} \frac{p\dot{M}_0}{4\pi R_* v_{s\infty}} \frac{ds}{x_s^2(t)}, \qquad (8.2)$$

where X is the number fraction of hydrogen atoms in the shell, $m_{\rm H}$ the mass of a hydrogen atom, $A_{\rm E}$ is the abundance (by number) of element E relative to hydrogen, $n_i/n_{\rm E}$ is the fraction of atoms of element E in ionization stage i, and ds and $x_s(t)$ are the thickness and distance (measured from the stellar center) of the shell, respectively, both in units of the radius of the star R_*.

The thickness of the shell is in first order proportional to the formation time τ. For simplicity we assume that the thickness remains constant during the lifetime of the shell. We also assume that the mass-loss enhancement factor p is constant during the formation. When the shell undergoes no further acceleration we may write

$$N_{\rm H} \propto \frac{n_i}{n_{\rm E}} \frac{\tau p}{t^2}, \qquad (8.3)$$

which shows that the column density will decrease as t^{-2} provided that the ionization is fixed.

The mass in the shell is given by

$$M_s = 4\pi R_*^2 x_s^2 m_{\rm H} N_{\rm H}, \qquad (8.4)$$

where for the calculation of $N_{\rm H}$ the abundance as well as the ionization fraction should be known. The (dimensionless) distance x_s can be estimated from the time that the shell has been visible and from its velocity. Combination of equations (8.3) and (8.4) gives a value for the product τp.

It would be very important to derive from the observations a separate estimate for the formation time τ and the mass-loss enhancement factor p. This would give some handle on the physical cause of the episodic mass loss in the proposed model. At present, however, we do not know how to obtain these estimates. A value for τ might be derived from the thickness of the shell. Close to the star the shell will be strongly curved which will broaden the absorption. In principle the broadening parameter contains a contribution from geometrical distortion, but separation of this effect from the additional broadening effects is in practice impossible (especially a velocity gradient across the shell).

d) *Confrontation with Observations*

The initially rapid rise of velocity, which is a general property of any proposed and/or derived velocity law, explains why most of the narrow lines are observed at or near the terminal velocity of the shell. The steeper the velocity law, the smaller the probability of observing the shell below its terminal velocity.

We showed in § VIII*b* that the observed relation between the column density in each different episode and the central velocity of narrow lines (Figs. 6 and 8) is in quantitative agreement with a radiation-pressure driven wind model if not all driving lines are saturated. This relation is also expected when the column densities are constant, but, as we propose, can also be explained by assuming a column density that is a strongly decreasing function of time. In that case the relation is found because the column density lasts the longest time at the lower value.

In γ Cas the time series in 1980 March–April showed indeed that the column density is a strongly decreasing function of time and that the central velocity of the narrow lines hardly changes. Figure 3*b* shows this clearly. A possible interpretation of the decay of the column density in the form of two different shell episodes is given in Paper II. We realize that this interpretation is not completely unambiguous, because the first spectrum of the time series does show three components in the C IV and N V lines. The broadest component does have the lowest velocity (-650 km s^{-1}) which may indicate a geometrical distortion effect.

In Paper II we derived the values $\tau p \approx 50$ and 5 for the presumedly two shells in the time series (the formation time τ of the shell is expressed in days.) These values are based on the assumption that 10% of Si is in Si IV. If this fraction is higher, the values for τp are correspondingly to be increased. If the formation time is much longer than a day (for instance, a week or longer), we would have expected many more narrow absorption features at low velocities than we have observed in γ Cas. The conclusion is that a high value of τp means that the mass-loss enhancement factor p must be very high, at least much higher than the mass loss variations of a factor of 2 as reported by Snow, Wegner, and Kunasz (1980).

IX. DISCUSSION

Observational tests for the proposed (phenomenological) UV-shell model would have to come from UV spectra taken with high time resolution ($\sim 1/2$ hour) during the presumed formation of a shell. As the origin of this enhanced mass loss is not understood, no prediction can be made as to when such an episode will occur. From Figure 7 we infer a mean interval between the episodes of about a month for γ Cas.

LGS also considered the possibility that the narrow components observed in their sample of stars are due to variable mass loss. They concluded from the study of column densities that this explanation is unlikely because it would imply either (*a*) a very frequent ejection of shells (about once per day), or (*b*) optically very thick shells ejected during phases when the mass-loss rate was at least a factor of 10 higher than normal. They rejected this hypothesis, however, because of the observational constraint that mass-loss variations by only a factor of 2 have been reported in Hα (Snow, Wegner, and Kunasz 1980). We notice, however, that the probability of observing the enhanced mass-loss rate in Hα during the formation of a shell is quite low, because the event will be very short (typically a few hours). Soon after its ejection the shell will not be observable in Hα, even when a temperature as low as 10^4 K in the shell is assumed (G. L. Olson 1980, private communication), the main reason being its low density.

It is interesting to mention that simultaneous UV and Hα variability has been reported by Slettebak and Snow (1978). These authors described a sudden and significant increase and decrease (within 100 minutes) of Hα simultaneously with a significant flux change (interpreted as emission) near the centers of the Si IV doublet lines (1977 January 26/27). Peters (1982*b*) reported that with the X-ray detector on board the *Copernicus* satellite an unusually large X-ray outburst was detected 3.5 hours *earlier*. The same X-ray burst was also observed with *Ariel V* (McHardy and Pye 1981 and McHardy 1981). Why the Hα and Si IV spectral changes should be related to this X-ray burst is not clear. It might be a reprocessing effect where the delay time is caused by the reprocessing time of the X-rays preceded by the travel time between a possible compact object and the regions where Hα and Si IV are formed.

If γ Cas is indeed member of a wide binary containing a neutron star, as has been suggested by Marlborough, Snow, and Slettebak (1978) and White *et al.* (1982), the intriguing possibility is opened of testing the UV-shell model as well as establishing the orbital separation. Strongly enhanced X-ray emission should follow the ejection of a shell, delayed by the (observable) travel time of the shell. In this respect it is significant that at least two strong X-ray outbursts have been reported from γ Cas (McHardy 1981). The observed X-ray variability in sources identified with OB stars might also be explained, in this way, by the UV-shell model.

It is possible to calculate the energy deposited by the steady wind when it hits the more slowly moving shell. Taking 1700 km s^{-1} and 1300 km s^{-1}, respectively, for the velocities and adopting a mass-loss rate of 10^{-8} $M_\odot$ yr^{-1}, the result is an energy rate of 5×10^{32} ergs s^{-1}, in perfect agreement with the observed X-ray energy flux from γ Cas. However, in the strong shock limit, the postshock temperature will be about 3×10^6 K. This is too low to account for the observed X-ray spectrum which would imply about 10^8 K (White *et al.* 1982). The energy could be lost by either accelerating the shell or heating the gas, but both effects are probably of minor importance. Another possibility is that not so much energy is released because the shell might be clumpy.

Not much is known about a possible origin of the proposed episodic mass-flux enhancement. Several recent theoretical investigations have shown that line-driven stellar winds are unstable (Lucy and White 1980; Carlberg 1980; Kahn 1981; Lucy 1982). These analyses, however, concentrate on the X-ray production throughout the stellar wind due to shock heating or decay of turbulent energy. If we want to identify one of those predicted instabilities with the occurrence of the observed narrow components, we find that the instability that gives rise to large-scale convective motions superposed on the upward stellar wind flow as described by Kahn (1981) is probably the only solution which is compatible with the properties of the presumedly enhanced mass flux. Kahn's instability analysis predicts density perturbations in antiphase with the velocity perturbations and in the radial component of velocity. This is indeed suggested by our Figs. 6 and 8, in which a higher density is correlated with a lower velocity, i.e., with a larger velocity perturbation with respect to the "steady" stellar wind and in opposite direction. We notice that the line shape, radiation-driven soundwave and gradient instabilities found by Carlberg (1980) cannot be associated with the narrow components because in these instabilities density and velocity perturbations are always in phase, in contrast to what is observed in the narrow components. If Kahn's instability analysis applies to the phenomenon of the narrow lines, the above given results have to be modified because our analysis is based on the assumption of spherical symmetry (because of simplicity). If indeed large turbulent cells occur in the wind, this would give strong deviations from the spherical case, and one of the consequences would be that the column density would not decay according to t^{-2} but less steeply (i.e., slower). Unfortunately, the limited amount of available observations (see also Paper II) allows no direct determination of the power in this relation, but such a less strong time dependency might well explain why the narrow components are visible for a relatively long time without the requirement of an exorbitantly high mass-loss enhancement. A less steep decay would also explain more easily why in Figure 8 the scatter is relatively small. It is clear, however, that only observations with high time resolution and/or over a long time interval would give a possible answer to this important question and would allow a more detailed numerical comparison with Kahn's analysis.

We may estimate how much the episodic mass ejection contributes to the overall mass loss from the star. If we suppose a mean ejection rate of one UV-shell every month with each a mean value of $\tau p = 30$, we obtain as a result that the amount of episodic mass loss is comparable to the amount of steady mass loss and hence that the total mass-loss rate from the star will probably not be significantly affected. We notice that this would not be in conflict with the supposition of enhanced mass loss from the star due to instabilities in the stellar wind, because it is unlikely that such an instability would give rise to a much higher overall mass loss.

Finally, we emphasize that we did not try to model all the observed properties of the Be star γ Cas. Instead, we proposed that the occurrence and variability of the high-velocity, narrow absorption components that are often observed in P Cygni lines of species of high ionization, are general properties of Be stars (in particular γ Cas) as well as of other (non-Be) stars of early type. We propose that the occurrence of these narrow absorptions indicates variable mass loss. This type of mass loss is in this model not correlated with the Be phenomenon. Further study of the narrow lines in a sample that should include B and Be stars, might reveal a possible relation between the Be phenomenon and, for instance, the frequency of reappearance and/or strength of the narrow absorptions in these stars.

H. F. H. wishes to thank Professor R. Wilson and members of his department for their hospitality during his visit to University College London. The authors are especially grateful to Jack Giddings for his helpful advice during the reduction of the spectra. The authors thank M. Marlborough and G. Hill for communicating *IUE* spectra of γ Cas, I. McHardy for sending *Ariel V* data prior to publication, G. Olson for making a calculation of Hα profiles, G. Peters and N. White for timely reprints, and in particular A. J. Willis for his continuous interest in and support of this project. Section VII of the manuscript profited from remarks by V. Doazan. The authors enjoyed many inspiring discussions with H. J. G. L. M. Lamers during the course of this investigation, and they thank him as well as A. Hearn and E. van den Heuvel and in particular Jan Kuijpers for their comments and critical reading of the manuscript. The figures were carefully drawn by E. I. Faverey.

G. H.-H. acknowledges support from the Netherlands Foundation for Astronomical Research (ASTRON) with financial aid from the Netherlands Organization for the Advancement of Pure Research (Z. W. O.).

Note added in manuscript.—After submission of this paper a preprint by A. B. Underhill and R. P. Fahey was received in which the narrow lines are proposed to be connected with bipolar magnetic regions on the surface of early-type stars.

REFERENCES

Abbott, D. C. 1978, *Ap. J.*, **225**, 893.
Barlow, M. J., and Cohen, M. 1977, *Ap. J.*, **213**, 737.
Beals, C. S. 1951, *Pub. Dom. Ap. Obs.*, **9**, 1.
Boggess, A., *et al.* 1978*a*, *Nature*, **275**, 372.
Boggess, A., *et al.* 1978*b*, *Nature*, **275**, 377.
Bohlin, R. C. 1970, *Ap. J.*, **162**, 571.
Carlberg, R. G. 1980, *Ap. J.*, **241**, 1131.
Castor, J. I, Abbott, D. C., and Klein, R. I. 1975, *Ap. J.*, **195**, 157.
Castor, J. I., and Lamers, H. J. G. L. M. 1979, *Ap. J. Suppl.*, **39**, 481.
Cowley, A. P., and Marlborough, J. M. 1968, *Pub. A.S.P.*, **80**, 42.

Cowley, A. P., Rogers, L., and Hutchings, J. B. 1976, *Pub. A.S.P.*, **88**, 911.
Doazan, V. 1982, in *B Stars with and without Emission Lines*, ed. A. B. Underhill and V. Doazan (NASA Monograph Series SP-456), p. 450.
Doazan, V., Grady, C., Kuhi, L. V., Marlborough, J. M., Snow, T. P., and Thomas, R. N. 1982, in *IAU Symposium 98, Be Stars*, ed. M. Jaschek and H.-G. Groth (Dordrecht: Reidel), p. 415.
Doazan, V., Kuhi, L. V., and Thomas, R. N. 1980, *Ap. J. (Letters)*, **235**, L17.
Doazan, V., Selvelli, P., Stalio, R., and Thomas, R. N. 1980, in *Proc. Second European IUE Conf., Tübingen*, ed. B. Battrick and J. Mort (ESA SP-157), p. 145.
Drechsel, H., and Rahe, J. 1982, *Astr. Ap.*, **106**, 70.
Ferlet, R., Laurent, C., Vidal-Madjar, A., and York, D. G. 1980, *Ap. J.*, **235**, 478.
Giddings, J. 1981, *ESA IUE Newsletter*, **12**, 22.
Grady, C. A., Snow, T. P., and Cash, W. C. 1982, in preparation.
Hamann, W. R. 1980, *Astr. Ap.*, **84**, 342.
Hammerschlag-Hensberge, G. 1979, *IAU Circ.*, 3391.
Hammerschlag-Hensberge, G., *et al.* 1980, *Astr. Ap.*, **85**, 119.
Henrichs, H. F. 1982, in *IAU Symposium 98, Be Stars*, ed. M. Jaschek and H.-G. Groth (Dordrecht: Reidel), p. 431 (Paper II).
Henrichs, H. F., Hammerschlag-Hensberge, G., and Lamers, H. J. G. L. M. 1980, *Proc. Second European IUE Conf., Tübingen*, ed. B. Battrick and J. Mort (ESA SP-157), p. 147 (Paper I).
Holm, A. 1979, *NASA IUE Newsletter*, **7**, 27.
Howarth, I. D. 1979, *J. British Astr. Soc.*, **89**, 4, 378.
Kahn, F. D. 1981, *M.N.R.A.S.*, **196**, 641.
Lamers, H. J. G. L. M. 1981, *The Universe at Ultraviolet Wavelengths*, ed. R. Chapman (NASA Conf. Pub. 2171), p. 93.
Lamers, H. J. G. L. M., Gathier, R. and Snow, T. P. 1982, *Ap. J.*, **258**, 186 (LGS).
Lamers, H. J. G. L. M., and Morton, D. C. 1976, *Ap. J. Suppl.*, **32**, 715.
Lesh, J. R. 1968, *Ap. J. Suppl.*, **17**, 371.
Lucy, L. B. 1982, *Ap. J.*, **255**, 286.
Lucy, L. B., and Solomon, P. 1970, *Ap. J.*, **159**, 879.
Lucy, L. B., and White, R. L. 1980, *Ap. J.*, **241**, 300.
Marlborough, J. M. 1977, *Pub. A.S.P.*, **89**, 122.
Marlborough, J. M., Snow, T. P., and Slettebak, A. 1978, *Ap. J.*, **224**, 157.
McHardy, I. M. 1981, private communication.
McHardy, I. M., and Pye, J. P. 1981, *Space Sci. Rev.*, **30**, 457.
Panek, R. J., and Savage, B. D. 1976, *Ap. J.*, **206**, 167.
Peters, G. J. 1982*a*, *Ap. J. (Letters)*, **253**, L33.
______. 1982*b*, *Pub. A.S.P.*, **94**, 157.
Poeckert, R., and Marlborough, J. M. 1977, *Ap. J.*, **218**, 220.
______. 1978, *Ap. J.*, **220**, 940.
Poeckert, R. and van den Bergh, 1982, *Pub. A.S.P.*, in press.
Purton, C. R. 1976, in *IAU Symposium 70, Be and Shell Stars*, ed. A. Slettebak (Dordrecht: Reidel), p. 157.
Rottenberg, J. A. 1952, *M.N.R.A.S.*, **112**, 125.
Scargle, J. D., Erickson, E. F., Whitteborn, F. C., and Strecker, D. W. 1978, *Ap. J.*, **224**, 527.
Schmidt-Kaler T. 1964, *Veröff. Astr. Inst. Univ. Bonn*, No. 70.
Secchi, A. 1867, *Astr. Nachr.*, **68**, 63.
Settle, J. and Sanford, M. C. W. 1980, *UK IUE Newsletter*, **5**, 7.
Slettebak, A. 1982, *Ap. J. Suppl.*, **50**, 55.
Slettebak, A., and Snow, T. P. 1978, *Ap. J. (Letters)*, **224**, L127.
Snow, T. P. 1977, *Ap. J.*, **217**, 760.
______. 1979, in *IAU Symposium 83, Mass Loss and Evolution of O-Type Stars*, P. S. Conti and C. W. H. de Loore (Dordrecht: Reidel), p. 65.
______. 1981, *Ap. J.*, **251**, 139.
Snow, T. P., and Jenkins, E. B. 1977, *Ap. J. Suppl.*, **33**, 269.
Snow, T. P., Peters, G. J., and Mathieu, R. D. 1979, *Ap. J. Suppl.*, **39**, 359.
Snow, T. P., Wegner, G. A., and Kunasz, P. B. 1980, *Ap. J.*, **238**, 643.
White, N. E., Swank, J. H., Holt, S. S., and Parmar, A. N. 1982, *Ap. J.*, **263**, 277.
York, D. G., Vidal-Madjar, A., Laurent, C., and Bonnet, R. 1977, *Ap. J. (Letters)*, **213**, L61.

G. Hammerschlag-Hensberge and H. F. Henrichs: Astronomical Institute, University of Amsterdam, Roetersstraat 15, 1018 WB Amsterdam, The Netherlands

P. Barr and I. D. Howarth: Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, England