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NONRADIAL OSCILLATIONS OF THE Be STAR GAMMA CASSIOPEIAE

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ABSTRACT

Subfeatures $< 0.5\%$ of continuum were detected moving through the line profiles of the Be/shell star γ Cas over a nine-month period in 1983. While the average spacing and acceleration of the subfeatures is consistent with nonradial pulsation of $|m| = 12 \pm 4$, large variations in the acceleration of the subfeatures are sometimes seen and some subfeatures appear and disappear suddenly. The subfeatures appeared particularly chaotic on 1983 October 26, five days prior to detection of a strong X-ray flare with the *Tenma* satellite. The observed period of the subfeature oscillations varies between 7000 and 10,000 seconds which is similar to the transient 6000-second variation in X-ray flux found by *EXOSAT* in December 1984. No rapid *E/C* variation is observed in the Hγ and He I λ5876 emission-line profiles.

Key words: Be stars–nonradial pulsations

I. Introduction

B-type stars of luminosity classes III to V which have superimposed Balmer emission are generally defined as Be stars. Some Be stars also show emission in singly ionized metallic lines such as Fe II. It is generally accepted that the Be phenomenon is only one of a series of phases that this type of star may pass through. At other epochs, it can go into a shell phase with sharp shell lines in the visible region. The same star can also exhibit a quasi-normal-B phase stellar spectrum. A detailed review can be found in Doazan (1982). Other recent reviews of Be/shell stars are Hutchings (1976), Slettebak (1979, 1982), De Jager (1980), Kogure and Hirata (1982), Kitchen (1982), Doazan and Thomas (1983), Harmanec (1983), Hirata and Kogure (1984), and Dachs (1987).

The optical spectra of Be/shell stars are known to vary over time scales of years. The variations include the transformation of the star between the various phases, the *E/C* (ratio of the emission in the lines to the adjacent continuum) variations, and the *V/R* (ratio of the violet-to-red emission peaks) variations. The radial velocities have also been known to vary on time scales ranging from a few days to years or decades. Early reports of irregular rapid spectroscopic and photometric variations on time scales of hours and even minutes are summarized in Lacy (1977), Slettebak and Reynolds (1978), and Slettebak (1982). However, the reality of these early rapid variations have been questioned (Lacy 1977; Clarke and Wyllie 1977).

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The star ζ Ophiuchi was the first Oe star found to have rapid periodic line-profile variations attributed to nonradial pulsations (Walker, Yang, and Fahlman 1979; Vogt and Penrod 1983). Rapid periodic or quasi-periodic changes in the spectrum of the Be star ω Canis Majoris have been reported by Baade (1982*a*,*b*) where they are also attributed to nonradial pulsations. Several other Be stars have subsequently been reported to exhibit similar rapid quasi-periodic line-profile variations: 10 Canis Majoris (Baade 1984*a*), μ Centauri (Baade 1984*b*), HR 4074 (Baade 1984*a*), and λ Eridani (Smith, Gies, and Penrod 1987). Rapid periodic photometric variations of a number of Be stars have also been attributed to nonradial pulsations (Percy 1986).

It has been suggested that the Be phenomenon may be related to the nonradial pulsations of these stars (Penrod 1986; Penrod and Smith 1985). This is based partially on the observed correlation between pulsation amplitudes and the occurrence of Be outbursts for λ Eri (Bolton 1982; Penrod 1986, 1987) and for ζ Oph (Vogt and Penrod 1983). A possible mechanism for a low-l pulsation mode to produce a Be outburst has been outlined by Penrod (1986). Willson (1986) has discussed the application of nonradial pulsations in Be stars to produce a "hot corona", a cool disk-like structure (material concentrated at the equatorial plane), and possibly a "hot" coronal "cap" in the polar regions. Reviews of nonradial pulsation theory of massive stars are given by Osaki (1986) and Cox (1986) and of nonradial pulsation in Be stars by Percy (1986, 1987), Smith (1986*b*), and Baade (1987).

Penrod and Smith (1985) speculated that pulsation modes of increasing l are excited during an outburst. Baade (1984*b*) has already reported the existence of an $l =$

10 mode in μ Cen. It is the purpose of this paper to report the existence of a high-l mode in γ Cas.

In addition to being the first-discovered emission-line star (Secchi 1867), γ Cas (HR 264, HD 5394, ADS 782A), the brightest Be star in the Northern Hemisphere, is also one of the most frequently observed. The underlying star has a spectral type of B0 IV (Hoffleit and Jaschek 1982) and a $V_e \sin i$ of about 300 km s^{-1} (Hutchings and Stoeckley 1977). Over the last 120 years, γ Cas has displayed all three phases of a Be/shell star: Be, B shell, and quasi-normal B (De Jager 1980; Doazan 1982). Recent photometric results are given by Bohme (1985, 1986) and Kilambi, Rao, and Sarma (1987), and additional spectroscopic results in Galkina (1981), Fontaine *et al.* (1982), Henrichs *et al.* (1983), and Doazan *et al.* (1983, 1984, 1987). The many phenomena observed in γ Cas and their time scales are summarized in Kogure and Hirata (1982). γ Cas has also been identified with the variable hard X-ray source MX 0053+60 (Jernigan 1976). The presence of a compact companion has been suggested by White *et al.* (1982). From observations with the *Tenma* satellite of the 6.8 keV iron line, Murakami *et al.* (1986) suggested that the companion is a white dwarf. Frontera *et al.* (1987), on the other hand, felt the case for a neutron star in a wide orbit is more consistent with the observations. To date, there has been no supporting evidence for binarity from radial-velocity measurements of γ Cas (Cowley, Rogers, and Hutchings 1976).

Besides rapid variations in X-ray (Peters 1982), linear polarization (Piirola 1979), and ultraviolet lines (Marlborough, Snow, and Slettebak 1978), there have been numerous reports of rapid variations in the Balmer emission-line profiles: Hutchings (1967, 1968), Clarke, McLean, and Wyllie (1975), Cowley *et al.* (1976), Doazan (1976), and Hu, Sun, and Dong (1985). Hutchings (1970) also reported a 0.7-day period in the V/R variations of Hβ and Hγ. However, there have also been reports of null detections of variability: Schoembs and Spannagl (1976), Kitchin (1976), and Hubert *et al.* (1987).

Using a Reticon detector, Chalabaev and Maillard (1983) found no evidence of rapid line-profile variations in Hα and the lines in the λ8500 region at a level of 1%–2% of the stellar continuum. Similarly, Fontaine, Lacombe, and Wesemael (1983) found no evidence of rapid variability in the Hα line profile greater than 0.5% of the continuum. In this paper we report detection of rapid line-profile variations for many of the lines in γ Cas at levels of less than 0.5% of the continuum.

II. The Observations

Time series of spectra were obtained with the coudé spectrograph of the Dominion Astrophysical Observatory 1.22-m telescope using a refrigerated RL1872F/30 EG&G Reticon as detector (Walker, Johnson, and Yang 1985). The grating which is blazed at 5000 Å has a reciprocal dispersion of about 10 Å mm^{-1} in the first order. This corresponds to a dispersion of about 0.14 Å per pixel on the Reticon array and a spectral coverage of about 270 Å.

Spectral time series were obtained on five nights in 1983. The major spectral lines studied are Hγ, He I λ4388, λ4471, λ5876, and Si III λ4552. Many weaker and often blended lines are also present. Table I lists the number of spectra (N) in each time series, the mean S/N per pixel in the stellar continua, the mean exposure time per spectrum, and the spectral coverage of each time series. The time coverage in each time series is essentially N times the mean exposure time. In the case of October 26, this is about ten hours or 0.42 day of continuous observations.

The data reduction was performed using the program RETICENT (Pritchet, Mochnacki, and Yang 1982). The technique of preprocessing the Reticon spectra to obtain the optimum S/N has been described in Walker *et al.* (1985). Barycentric corrections for the wavelengths and times are made using the algorithms given in Stumpff (1980).

III. The Line-Profile Variations

The data from July 23 have been presented in Ninkov, Yang, and Walker (1983). The time series of He I λ4471 line profiles from October 26 are shown in Figure 1(a). All spectra have been smoothed by a Gaussian transfer function with a σ value of 0.105 Å. Despite the small line depths, very minute changes in the line profiles can be detected because of the high S/N of the data. One can readily conclude that the variations occur at much smaller amplitudes than those observed in ζ Oph (Walker *et al.* 1979), α Virginis (Walker *et al.* 1982), and μ Cen (Baade 1984*b*). The variations are best seen in the residuals shown in Figure 1(b) which were formed by subtracting an average line profile from each spectrum. The variations are at less than 0.5% of the continuum, and take the form of subfeatures moving systematically from blue to red across the line profiles. This behavior is very similar to that observed in α Vir and is generally attributed to nonradial pulsations of the star (Smith 1985).

TABLE I

The Observations

Date (UT)	Exposure (s)	N	S/N	Spectral Region
04/Mar/83	830	9	872	$\lambda\lambda$5670-5940
05/Mar/83	1040	11	1075	$\lambda\lambda$5670-5940
23/Jul/83	1000	23	1090	$\lambda\lambda$4250-4530
26/Oct/83	1000	36	1220	$\lambda\lambda$4320-4590
21/Nov/83	1000	17	1170	$\lambda\lambda$4450-4730

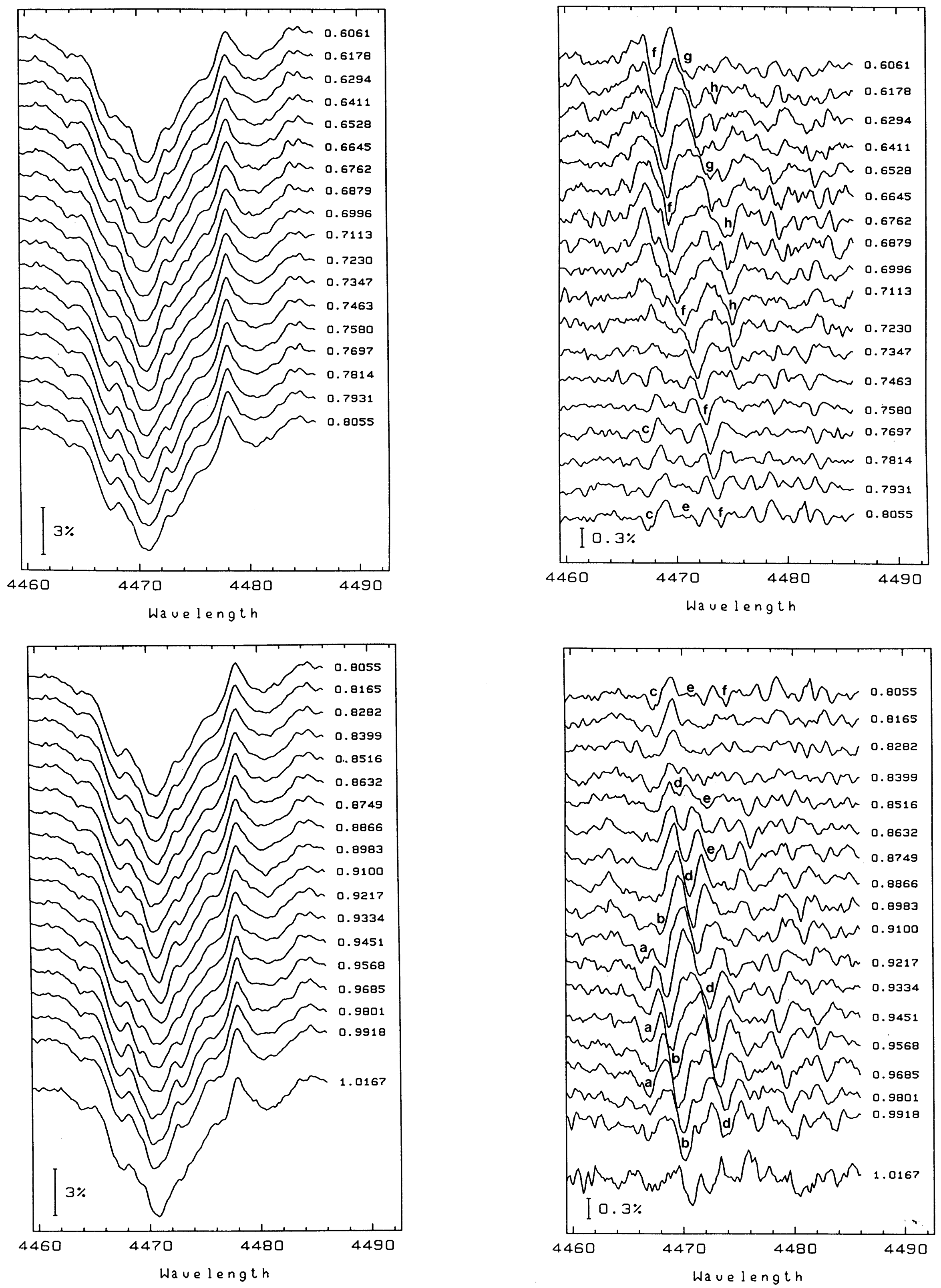

FIG. 1–(a) Spectral time series of the He I λ4471 line profiles observed on 1983 October 26 UT. The number at the right of each spectrum is the corresponding midexposure time in fractions of a day from the barycentric JD2445633. The percentage of the continuum is also indicated. (b) The residuals formed by taking the difference between the spectra in Figure 1(a) and the mean spectrum from the time series. The more prominent subfeatures are identified.

Figure 2(a) shows the Si III λ4552 and λ4567 lines with the corresponding residuals plotted in Figure 2(b). It is obvious from Figures 1(b) and 2(b) that a large number of subfeatures appear within the line profiles. The same

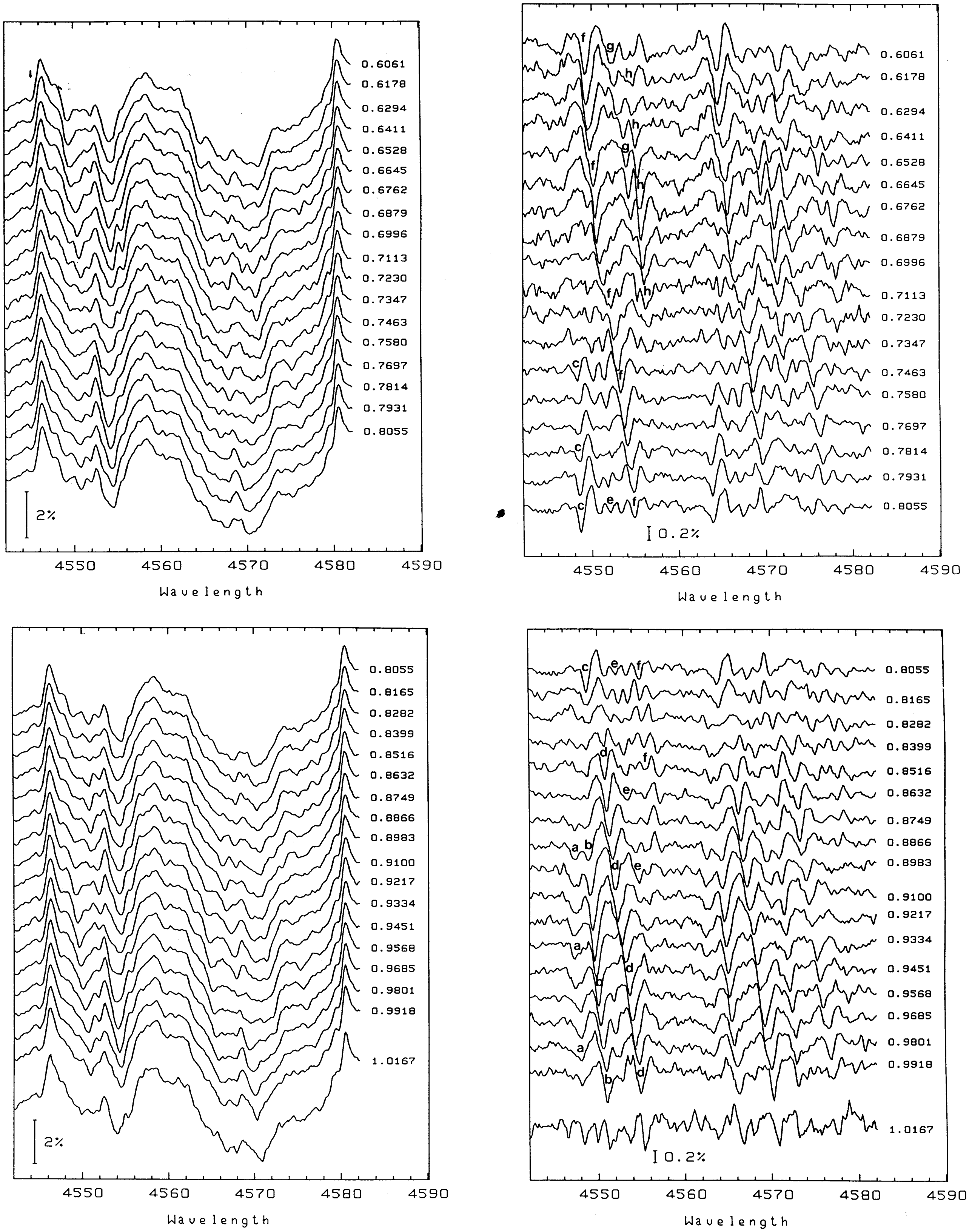

FIG. 2–As Figure 1 for the Si III λ4552 and λ4567 lines.

subfeatures can be identified in both lines and their general movements are also identical. The more prominent subfeatures in the Si III λ4552 line are labeled *a* through *h* in Figure 2(b). The corresponding subfeatures in the He I λ4471 line are also identified in Figure 1(b).

Since many of the subfeatures are very weak, one must exercise some judgment in defining them. In order to minimize subjective bias, we used an interactive graphic method which displays only one residual spectrum at a time to measure the positions of the subfeatures. Because of the smaller intrinsic linewidth and hence higher subfeature visibility, the movements of the subfeatures are more easily tracked in the Si III λ4552 line than the He I λ4471 line. The Si III λ4567 line is less suitable because it is blended with neighboring lines.

The displacement in velocity from the line center is shown in Figure 3 for all of the subfeatures detectable in the Si III λ4552 line of Figure 2(b). The adopted rest wavelength used in the velocity calculations is 4552.654 Å. An intrinsic radial velocity of -7 km s^{-1} (Hoffleit and Jaschek 1982) has also been assumed for γ Cas. Subfeatures *a* through *h* are identified on the plot. Figure 3 also shows a linear fit to the velocities for each subfeature.

One of the most striking phenomena in Figure 3 is the apparently large variation in the acceleration of subfeature *f* over several hours which is also obvious in Figures 1(b) and 2(b). There is no simple explanation for such a variation in terms of the nonradial pulsation theory. In Figures 1(b) and 2(b), there are several examples of the sudden appearance and disappearance of certain subfeatures. In Figure 3, the most striking is the sudden disappearance or damping of subfeature *c* which is followed almost immediately by the appearance of subfeature *d* at a slightly longer wavelength. Both subfeatures are quite strong and there is very little doubt about the reality of this phenomenon.

The unusual behavior of the subfeatures may be related to the spectral transients which have been discussed by Smith *et al.* (1987) in λ Eri. Many of these minor subfeatures may not arise in the stellar photosphere. If the inclination angle of γ Cas is about 45° as suggested by Poeckert and Marlborough (1978), one can observe phenomena in the photosphere and any circumstellar disk simultaneously which would confuse photospheric subfeatures with events in the circumstellar disk. Confusion by other excited modes is also a distinct possibility. Another possible explanation suggested by Smith (1986*a*) is the release of high-velocity matter into the photosphere by a subphotospheric pulsational instability.

The subfeature velocities for July 23 and November 21 are plotted in Figures 4 and 5, respectively. They do not show the vast number of unusual phenomena displayed in

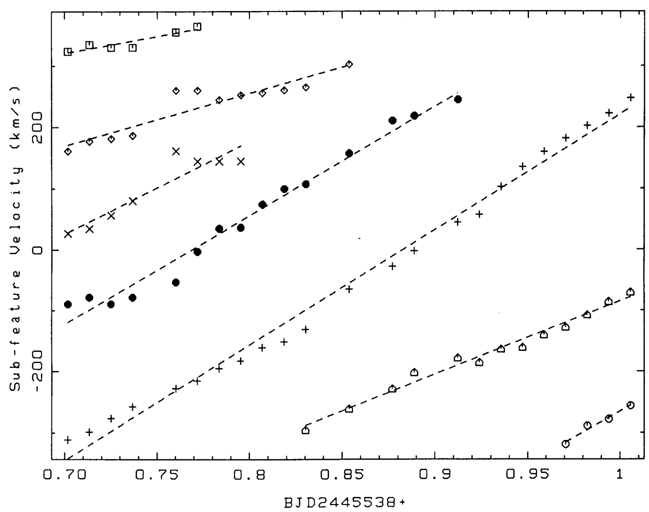

FIG. 4–Acceleration of all observed subfeatures in the He I λ4471 line from 1983 July 23 UT.

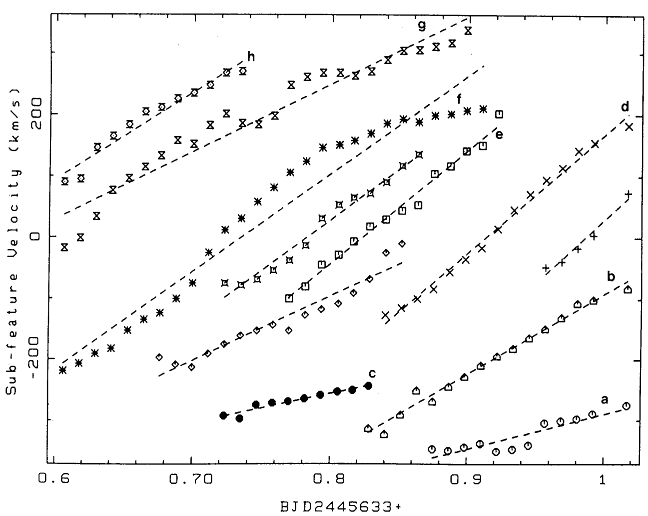

FIG. 3–Acceleration of all observed subfeatures in the Si III λ4552 line of Figure 2(b).

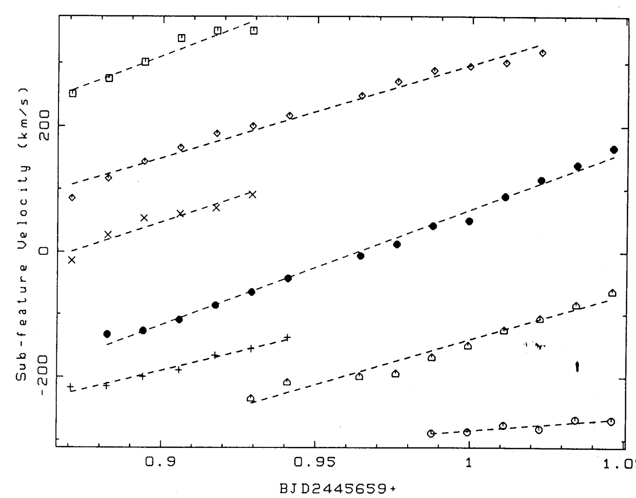

FIG. 5–Acceleration of all observed subfeatures in the Si III λ4552 line from 1983 November 21 UT.

Figure 3. This may be an indication that these phenomena on October 26 are probably transient events. It is interesting to note that a large X-ray flare was detected on October 31 (Murakami *et al.* 1986) but as they only monitored γ Cas from 1983 October 31 to November 2, it is not clear if the two phenomena are connected.

IV. Discussion

The observed line-profile variations are similar to those reported for many other rapidly-rotating early-type nonradial pulsators. Even the rapidly-rotating F-type δ Scuti nonradial pulsators found by Walker, Yang, and Fahlman (1987) show almost identical line-profile variations. Consequently, it is logical for one to suggest nonradial pulsation to be also a probable explanation for the observed line-profile variations in γ Cas. Other models, e.g., the occultation of the stellar photosphere by spokes in the circumstellar disk, have been tested against observational data of ζ Oph (Vogt and Penrod 1983) but they concluded nonradial pulsations are the most likely explanation. Ninkov *et al.* (1983) reported the absence of or much-reduced line-profile variations in some He II lines of ζ Oph. This is in spite of the fact that these He II lines, λ4541 and λ4686, are stronger than their adjacent lines of Si III and He I which show strong line-profile variations. We also find the same lack of line-profile variations in the He II λ4541 line of γ Cas. This is additional evidence that the observed line-profile variations in γ Cas are very similar to those attributed to nonradial pulsations in ζ Oph.

The observed pulsation frequency, σ, is related to σ_0, the intrinsic pulsation frequency in the corotating frame of the star by

$$\sigma \simeq \sigma_0 - m\Omega \ , \quad (1)$$

where Ω is the rotation frequency of the star and m is the azimuthal nonradial pulsation index. Equation (1) adopts the convention that $m < 0$ corresponds to prograde modes. If one assumes $\sigma \gg \sigma_0$ and sectorial-mode pulsation, i.e., $l = |m|$, then $|m|$ can essentially be determined by counting the number of nonradial wavecrests around the star (Walker *et al.* 1987)

$$|m| \simeq 2\pi (V_e \sin i)/(a_0 \Delta t) \ , \quad (2)$$

where a_0 is the acceleration of the subfeature at the line center and Δt is the average time delay between subfeature crossings. In units of cycles per day, σ is simply $1/\Delta t$. The approximation that $\sigma \gg \sigma_0$ is generally valid for rapid rotators with large m values. In the case of the $m = -16$ mode of α Vir, $\sigma_0 \simeq (0.07)\,\sigma$ (Smith 1985).

Table II lists the mean a_0 and Δt values from all the nights and the number of subfeatures n used in the calculations. Each a_0 is calculated as the mean acceleration of the n prominent subfeatures closest to crossing the line center. Similarly, each Δt is the mean time delay between each of these n subfeatures crossing the line center. The overall weighted mean a_0 and Δt are also given in Table II.

TABLE II

Sub-feature accelerations and time delays

Date (UT)	a_0 (kms^{-1}d^{-1})	Δt (d)	n
04/Mar/83	2350	0.117	2
05/Mar/83	1260	0.091	3
23/Jul/83	1720	0.100	3
26/Oct/83	1760	0.083	5
21/Nov/83	1730	0.089	5
mean	1730	0.091	23

Before using equation (2) to estimate m, one must know $V_e \sin i$. For γ Cas, Slettebak (1976) reports a value of 230 km s^{-1}, Hutchings and Stoeckley (1977) found a value of 300 km s^{-1} with $i = 47°$, while Poeckert and Marlborough (1978) found $V_e = 569$ km s^{-1}, $i = 45°$, and $R_* = 10\ R_\odot$. One can estimate a minimum value for $V_e \sin i$ from Figures 3, 4, and 5. If all the observed subfeatures are caused by nonradial pulsations in the photosphere, then the maximum observable velocity of these subfeatures is $(V_e \pm V_\phi) \sin i$, where V_e is the equatorial rotation velocity of the star and V_ϕ is the pulsation velocity amplitude in the azimuthal direction. The sign in front of V_ϕ depends on whether the pulsation is prograde or retrograde. Generally, $V_e \gg V_\phi$ and in the case of α Vir, $V_\phi \simeq 20$ km s^{-1} (Fahlman *et al.* 1987). Since the maximum velocity observed in Figures 3, 4, and 5 is about 350 km s^{-1}, the true $V_e \sin i$ value is probably somewhere between the two reported values of 300 and 400 km s^{-1}.

Using the mean a_0 and Δt from Table II, equation (2) was used to calculate $|m|$ values for different $V_e \sin i$ values. These are listed in Table III. If one assumes $\sigma \gg \sigma_o$, then equation (1) gives $|m| \simeq |\sigma/\Omega|$. In units of radians per second, Ω is simply V_e/R_*. Using the reported R_* value of 10 $R_\odot$ which is also consistent with the values given in

TABLE III

The m values

$V_e \sin i$ (kms^{-1})	$\|m\|$	$\|\sigma/\Omega\|$	$\|(0.9)\sigma/\Omega\|$
300	12.0	13.3	12.0
350	14.0	11.4	10.3
400	16.0	10.0	9.0

Underhill (1982) for stars of similar spectral types, a mean reported i value of 46°, and $\sigma = 1/\Delta t$, $|m|$ is also calculated in this manner for different $V_e \sin i$ values. These are again listed in Table III. If one assumes $\sigma_0 \simeq (0.1)\,\sigma$ ($\sigma_0 \simeq (0.07)\sigma$ in α Vir), then $|m| \simeq |(0.9)\sigma/\Omega|$. Estimates of $|m|$ using this particular method are listed in Table III. One fact that is very apparent from Table III is the large m values in all cases. The $|m|$ value can be as high as 16 or as low as 9, and a reasonable estimate is probably 12 ± 4. While we cannot determine i directly from our observations, the smaller amplitude of the subfeatures in γ Cas compared to either ζ Oph or α Vir could be related to the smaller value of i for γ Cas than for the other two stars.

Figures 6(a) and 6(b) show the ten-hour time series of the Hγ line profiles and the corresponding residual spectra, respectively. One can see the blue-to-red movement of the subfeatures across Hγ and the nearby O II λ4349 lines, but there is no obvious *E/C* variation in the Hγ emission-line profile greater than 0.2% of the continuum. This suggests that the previously reported rapid *E/C* variations may have been just transient events.

Figures 7(a) and 7(b) show the time series of the He I λ5876 emission-line profiles and the corresponding residuals, respectively. One can observe from Figure 7(a) that there are apparent *E/C* changes in the *V*-component of the emission line. However, in spite of the less-than-perfect cancellations of the narrow telluric lines, the residual plot indicates that these apparent changes are simply artifacts of subfeatures moving in the underlying absorption-line profile.

Oscillations in the X-ray flux of γ Cas with a period of about 6000 seconds were detected in December 1984 in a 22,000-second observation with *EXOSAT* by Frontera *et al.* (1987) but not in subsequent observations by Parma. Frontera *et al.* (1987) have suggested that the X-ray oscillations probably come from a neutron star in a four-year orbit and fed by the nonradial pulsations of the primary. Penrod and Vogt (1985) have also suggested for a similar X-ray Be binary system X Persei that nonradial pulsations cause periodic modulation in the structure of the stellar wind which in turn modulates the accretion rate and the X-ray luminosity. It is interesting that this period is close to the observed mean nonradial pulsation period, Δt, of about 8000 seconds. However, given the wide separation (~ 6 AU) between primary and neutron star, it is not clear how closely these two periods would be related.

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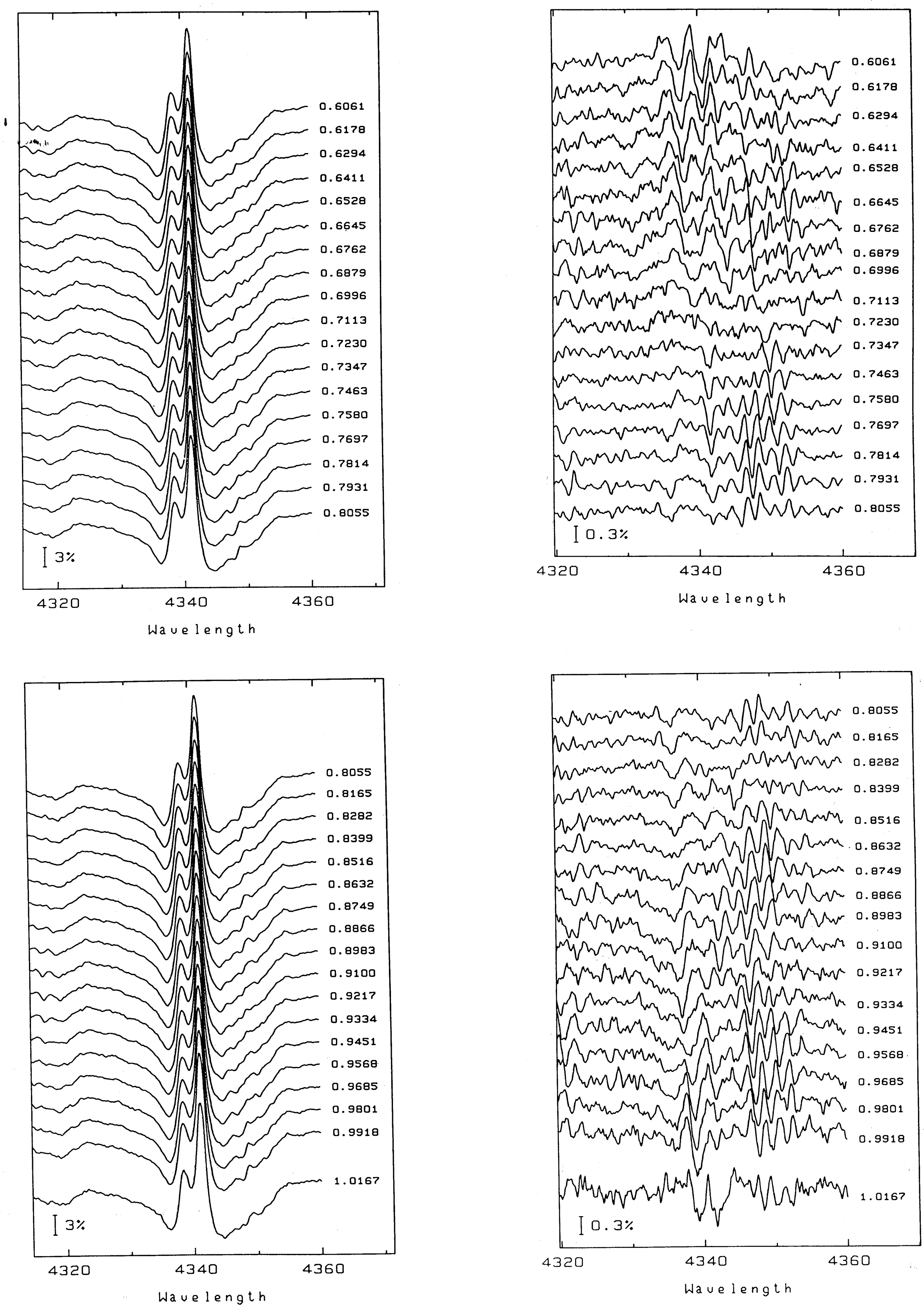

FIG. 6–As Figure 1 for the H I λ4340 line observed on 1983 October 26 UT.

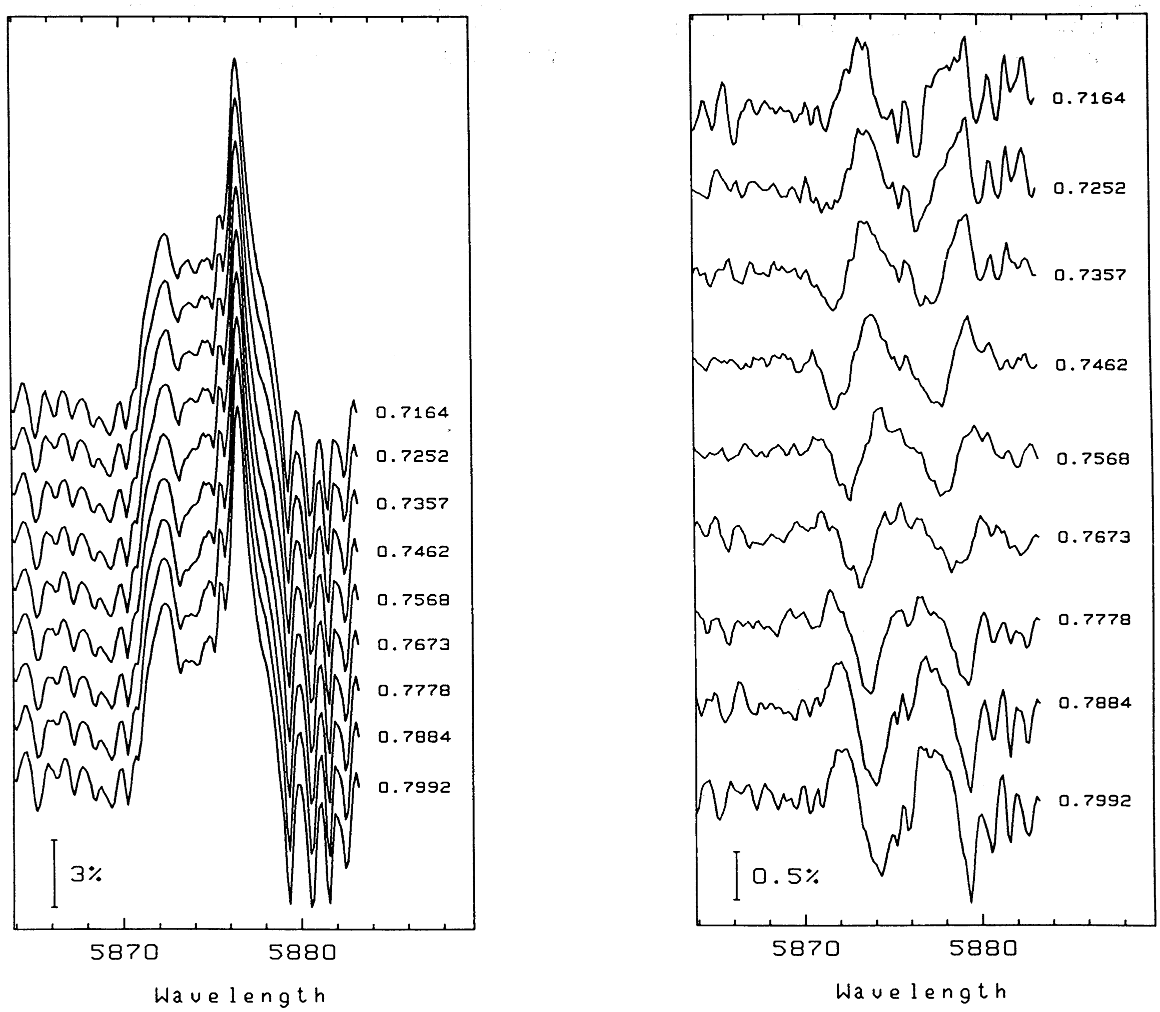

FIG. 7–As Figure 1 for the He I λ5876 line observed on 1983 March 4 UT. The number at the right of each spectrum is the corresponding midexposure time in fractions of a day from the barycentric JD2445397.

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