5. Be STARS:
SPECTROSCOPY AND PHOTOMETRY

PHOTOSPHERIC ACTIVITY IN SELECTED Be STARS: λ Eri AND γ Cas

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Abstract. Recent observations of rapid variations in optical He I lines, X-rays, and FUV wavelengths in the prototypical classical Be stars λ Eri and star γ Cas hint that the violent processes occur on the surfaces of these stars almost all the time. We suggest that of these phenomena show greater similarities with magnetic flaring than any other process thought to occur on stars.

1. Introduction

In retrospect, Peters' (1986) observation of the development of a high velocity feature in the λ6678 profile of μ Cen (B2e) was a call for the Be community to recognize that mass ejections of the surfaces of Be stars can occur discretely and violently over very rapid timescales. The extension of monitoring observations over several wavelength regimes, together with the development of multi-line spectroscopic detectors has brought necessary new tools to the search for the instability mechanism(s) in the atmospheres of classical Be stars. A reasonable strategy for investigating the local sites of mass ejections is to focus on a mild Be star the surface of which is visible most of the time because the outburst duty cycle is low, and a very active Be star seen at intermediate inclination. Examples of each of these categories are λ Eri (near edge-on, B2e; outburst duty cycle ~20 per cent) and γ Cas (B0.5e; in emission for 50 years), and I will confine my discussion to them. In addition to work by our group at Goddard, other teams have initiated *rapid* spectroscopic variability programs on these stars, e.g. in the U.S. (Gies, Peters), Canada (Kambe, Walker), Japan (Hirata), and India (Anandarao, Ghosh).

2. λ Eri's He I Line "Dimples"

In addition to regular line profile variations (*lpvs*) generally attributed to NRP, the He I λ6678 line of λ Eri shows an almost constant erratic activity which can be fit into a small group of patterns known as spectral transients (e.g. Smith 1989). At least 60 per cent of these events appear as central absorptions and weak flanking emissions known as "dimples" along the λ6678 profile. An additional ~10 per cent are "type d" or pure absorption events which are probably related to dimples. These features have a frequency of 0.2±0.05 events hr^{-1} and a duration of 2–4 hrs. They show a slow drift to the red during their lifetime. Occasionally, dimples have been observed to "come and go" over several hours, all the while moving along

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the profile consistent with the stellar rotation rate, as if caused by a rooted active spot on the surface. With the exception of two possible simultaneous dimples in the λ4922 line, dimples have been observed only in λ6678. Smith & Polidan (1993; SP) note that the λ6678 line in five other Be/Bn stars with $v \sin i \geq 250$ km s^{-1} show dimples. In a simultaneous optical/*IUE* campaign, SP discovered that 10–20 per cent weakenings of the C IV and N V resonance doublets were correlated with the appearance of λ6678 dimples. This discovery suggested plasma had been added along the line-of-sight with a density in between those in which the C IV and λ6678 lines normally form. This indication, along with the observation that the λ6678 line conserves its EW during a dimple appearance, led SP to investigate an *ad hoc* model for a dimple consisting of an opaque (in λ6678) stationary, detached, intermediate density "slab" over the surface of λ Eri that scatters line photons back toward the star. Photons scattered a second time in a "penumbra" surrounding the slab's projection on the surface acquire a doppler shift from the local projected rotational velocity, thereby redistributing photons from the central absorption part of the feature into wings with slightly enhanced emission. The model predicts the slabs' areas, elevations over the star, vertical velocity, and also permits estimates of slab densities. Typical slabs show areas of $\sim$3 per cent of the star's area, an elevation of $0.1R_*$, and a density of 10^{11-12} cm^{-3}. A slab cannot be associated with material moving with a vertical velocity exceeding the line width, for otherwise the slab will become transparent to λ6678 flux and the dimple will disappear. Typically, $V_{vert} \leq 30$ km s^{-1}. SP show that even some bizarre-shaped dimples with "inverse-P Cygni" profiles can be modeled with a slab falling at $\sim$35 km s^{-1} and also having an azimuthal component. If one assumes that 1.5 slabs are present somewhere over λ Eri's surface at any one time, they must comprise $\geq 3\times10^{-14}$ $M_\odot$. If dimples are visible in λ4922 the lower limit becomes 2×10^{-13} $M_\odot$. Given these masses, slabs should be just detectable over λ Eri as Hα emission (Marlborough, priv. comm.).

Dimples become optically thick within 15 mins. of onset (SP). This fact and the derived area means that the disturbance responsible for them propagates at $\sim$800 km s^{-1}, or about V_{esc}. One may discount formation scenarios requiring dimple-slabs to arise either from stellar ballistic ejections (dimples last too long) or from orbiting circumstellar debris (not long enough). Perhaps an Alfvenic disturbance propagates at this velocity, but this would not explain how plasma material can be transported at many times the sound speed to form a condensation. A paradigm that does account for many of the properties of slabs is the impulsive solar flare, which ejects a high energy plasma/electron beam to the chromo-/photosphere and heats it to a high temperature. The heated material evaporates from the surface at a velocity close to V_{esc} and encounters coronal magnetic loops, causing it to pile up there. The material cools to become a visible condensed prominence and eventually slowly falls back to the surface along field lines. The decay timescale for prominences is slow, ~2 days, compared to dimple lifetimes, but the formation timescale, density, and elevation over the Sun are similar to SP's estimates from modeling λ Eri's dimples.

Although the doppler integration models of dimples fit their shapes, we are unable to reproduce intensity line profiles from NLTE models with black line cores, as implicitly required by SP's backscattering model. This failure exemplifies the present lack of understanding of the physics of formation of these He I lines.

3. Multi Line Observations of Rapid Emission Activity in λ Eri

One way to study the line formation process is to compare and model the simultaneous response of several lines arising from the same atom. Toward this end we obtained (Smith *et al.* 1994) three nights of time series of KPNO fiber-echelle spectra of the first two members of the He I singlet/triplet 2P–nD series, viz. λ6678, λ4922, λ5876, and λ4471 when λ Eri happened to be in emission. Time serial observations of λ Eri, μ Cen, γ Cas and other stars in their active phases have demonstrated that emission features in He I lines (and sometimes even Hα) can show substantial variability in much less than the star's rotation period. λ Eri's λ6678 rapid emission variability often falls into one of several patterns that suggest the occurrence of failed ejections (see e.g. Smith 1989). This includes high velocity blue absorption components, emission shifting continuously from the V to the R wing on a timescale consistent with the ejection/infall velocities, and a correlation of blue absorptions followed shortly by red emissions. R emissions can even evolve into higher velocity absorptions as infalling material crosses the line of sight to the stellar disk (Smith *et al.* 1991; "SPG91"). Thin rings of material orbiting within 1R_* of the surface have also been noted (SPG91). It should therefore not be surprising that much of the V/R emission comes from matter projected over the limb matter. However, in general it is difficult to distinguish between emission produced by over-the-limb material and foreground matter with an enhanced source function. In the case of λ Eri, the potential exists for this ambiguity to be broken because R emissions tend to be stronger and because they are more prevalent than V emissions (Smith 1989).

The means to break the geometrical ambiguity was provided by simultaneous observations of several He I lines using Kitt Peak's 2.1-m echelle spectrograph on 1991 November 3–5 (Smith *et al.* 1994). We monitored the first two members of the singlet and triplet 2P–nD series, viz. λ6678, λ4922, λ5876, and λ4471. Our data showed contrasting behaviors of the V, R emission in the line wings and inner profile in this way: V emissions tend to scale with the line's log gf, with the blue lines showing small or no emission as

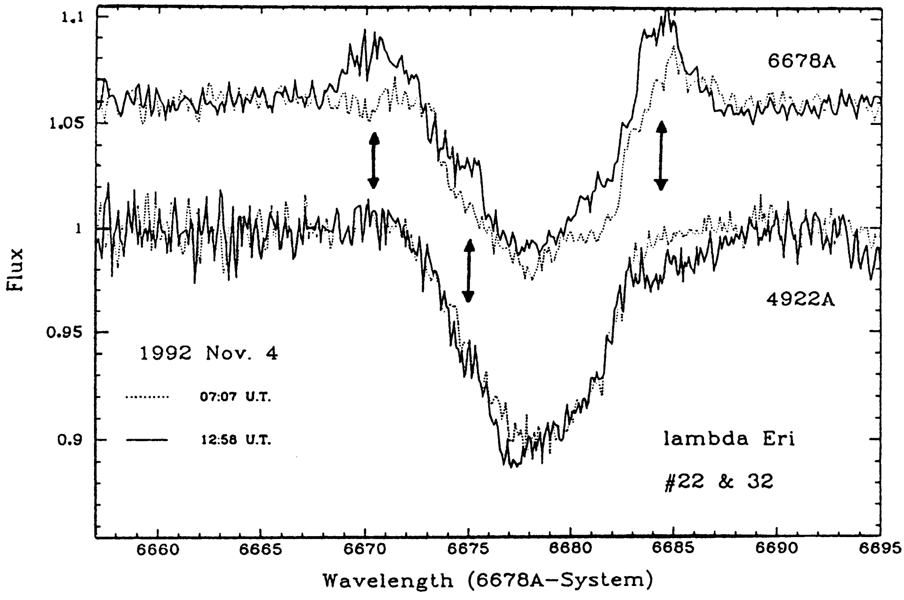

Fig. 1. λ Eri's R-wing fluctuations in emission (λ6678) and absorption (λ4922). Note V-wing/core emission in λ6678 compared to no change in λ4922.

the red lines varied from large to moderate emission strengths. Increases in R-wing emission correlated with definite weak ***absorptions*** in the V-wing of λ4922. When the "excess" emission wanes in λ6678 so does the absorption in λ4922. Fig. 1 shows an example of this contrasting behavior. Fig. 2 shows emission/absorption in the red cores of the two lines.

This behavior must necessarily be interpreted through NLTE processes affecting atoms in *foreground* material. Using the sophisticated NLTE code TLUSTY written by Hubeny (1988), Smith *et al.* (1994) were able to understand the simultaneous emission and absorption of these two lines by an NLTE effect first noted by Auer & Mihalas (1972) in hot atmospheres ($T_{eff} \geq 45000$K). At these temperatures, He I becomes a trace ion, causing the λ584 resonance line to become transparent and its radiation to leave the star. This drains electrons from the lower state of λ6678, 2^1P, thereby enhancing the source function of all transitions from this level. The effect is augmented for λ6678 by stimulated emission, driving the line almost preferentially into emission. Further study shows that this mechanism is confined to plasmas with at least a photospheric density. This is because at lower densities corresponding to the same ionization state the temperature and UV radiation field are too low to populate the upper atomic levels substantial-

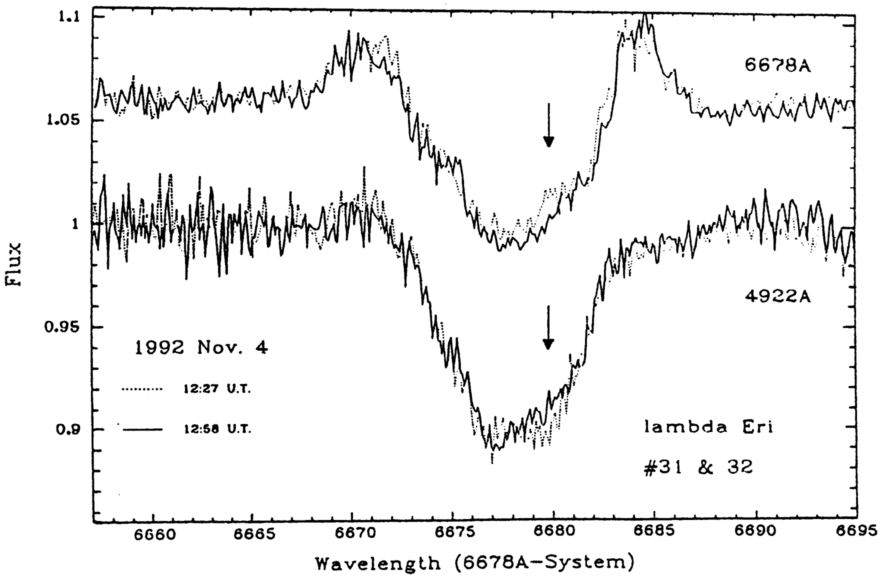

Fig. 2. Simultaneous em., abs. fluctuations in the red core of λ6678, λ4922.

ly, and this decreases the source function of all these lines. As Fig. 3 shows, the combination of λ6678 excess emission and λ4922 absorption confines the region of the (T_{eff}, log g) (i.e. T, N_e) domain further, requiring temperatures of at least 40000 K and densities of $\geq 10^{14}$ cm^{-3}. Another implication of this diagram is that the region where the required emission/absorption occurs does not coincide with the requirements for greatest efficiency of λ6678 emission. This implies that a much larger area of the star is responsible for λ6678 emission than if there were no λ4922 absorption. We plan to estimate typical hot spot areas in the near future.

The TLUSTY results imply that in contrast to the V-wing, the emission from the R-wing during λ Eri's outburst phase probably arise from downward-moving plasma within the atmosphere itself. It is easy to show from Virial Theorem arguments that the liberation of gravitational potential energy by infalling matter is too weak by $\geq 10^{4-5}\times$ to heat the implied hot spots on the star down to a level $\tau_c \sim 10^{-3}$. In contrast, there is enough CS mass around Herbig Be stars like HR 5999 to power the emission of lines by an infall mechanism (Blondel *et al.* 1993). In the energy hierarchy of astrophysical energy mechanisms, gravity is rather powerful. It dwarfs almost all other energy sources operating on stellar surfaces. We are able to think of only one other source (excepting nucleosynthesis), *viz.* flaring, that can produce more energy. Once again magnetic energy dissipation seems implicated as a destabilizing mechanism in the atmosphere of λ Eri.

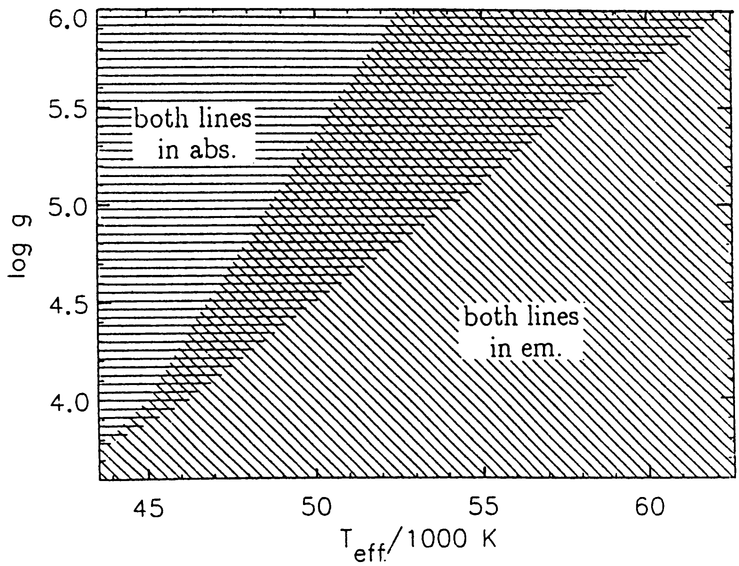

Fig. 3. T_{eff}, log g diagram, showing range of λ6678 emission, λ4922 absorption (cross-hatched region).

4. An X-Ray Flare on λ Eri

All this talk about possible flaring on λ Eri led us to request and be granted 29 Ksec of pointed (PSPC) observations with *Rosat*, an instrument capable of photon counting and spectral binning in the range 0.2–2 keV. Our observations were conducted on 1991 February 21–22 at the very beginning of the AO1/GO period with little notice to arrange simultaneous observations at other wavelengths. However, we were able to obtain an SWP camera *IUE* spectrum within several hours of the completion of the X-ray observations.

As detailed in Smith *et al.* (1993), our observations were distributed over 13 orbits spanning 38 hours. During the first two and last six orbits λ Eri was detected and showed a L_x/L_{bol} $\sim 2\times10^{-7}$ typical for an early B star. During the middle five orbits the X-ray flux rose to seven times its initial value; the e-folding timescale was $\leq$2 orbits. After reaching a peak $L_x = 4\times10^{31}$ ergs s^{-1}, the emission began declining, though with a slower decay rate. No significant fluctuations in emission were found on a shorter timescale. The final orbits of our timeline coincide with one rotational cycle after the maximum. Since the flux had returned to its initial state, one can rule out a rotationally modulated hot spot and characterize the brightening as an extended ($\sim$50,000 sec) flare, and a giant flare at that. The spectral analysis of our data shows the flare energy comes exclusively from photons having energies $\geq$ 0.7 keV and is characterized by a Raymond-Smith temperature of

1.4×10^7K and an Emission Measure of 3×10^{53} cm^{-3}. Both the temperature and EM of the softer component, presumably arising from the basal flux entirely, are each seven times smaller than the flare values.

The *IUE* spectrum showed a typically low wind flux for λ Eri, so that even if there was a hypothetical neutron star or white dwarf orbiting around this star too little X-ray flux would be emitted to account for the flare. As well as showing no detectable radial velocity variations that would betray binary motion, λ Eri's spectrum does *not* show traces of strong metal lines expected from a G–K dwarf capable of producing RS CVn-like or T Tauri flares. Smith *et al.* (1994) concluded that the best hypothesis was that this X-ray activity came from the Be star itself and probably from a flare-related process.

λ Eri is the second star to have been reported as an X-ray Be star; the first is γ Cas. The latter is well known to undergo rapid, chaotic X-ray fluctuations with a Raymond-Smith temperature of $\sim1.5\times10^8$K (Horaguchi *et al.* 1993, Parmar *et al.* 1993), if a thermal description is appropriate. Peters (1982) noted the first X-ray flare, an event on 1977 January 28 that was recorded as emission in several UV metallic lines as well as Hα (Slettebak & Snow 1978). Murakami *et al.* (1986) recorded a flare spectrum lasting several minutes and having a high temperature. Coincidentally or not, Yang et al. (1988) noted λ6678 line profile transients in observations a few days before this flare. Whereas the prevailing sentiment among the X-ray community is that γ Cas is a member of the group of X-ray Be binaries, the evidence for binarity is weak (no detectable RV variations; also, it has a symmetrical disk resolved by optical interferometry (e.g. Quirrenbach, these Proceedings.). Thus it does not fit into that group easily. Perhaps the best argument that γ Cas has a close degenerate companion is the high temperature of its X-ray spectrum. In most other respects the case for flares arising in Be stars, in our opinion, equals or outweighs the mass-accretion/neutron star scenario.

It is difficult to prove that γ Cas and λ Eri are typical Be stars. Why, for example, do surveys show early Be stars to be normal, even subnormal X-ray emitters, (Berghofer & Schmitt, these Proceedings.), when these two stars are so active? A possible explanation is that the X-ray emission occurs very close to the star and is attenuated by well developed Be disks. If so, the two stars we are discussing could be coincidentally good X-ray monitoring candidates either because the star's surface is usually visible or because X-ray flux is not absorbed by disks owing to a low aspect to our line of sight. We suggest that other low-sin$i$ Be stars, e.g. μ Cen, should be good candidates for X-ray monitoring.

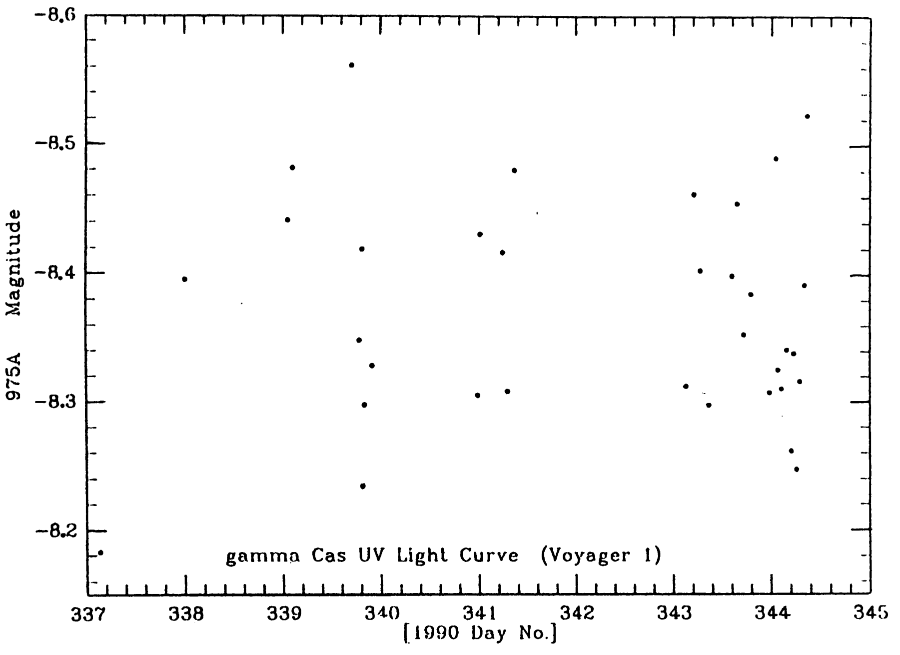

Fig. 4. **FUV rapid flux variations in γ Cas during 1990-1.**

5. Far-UV and X-ray Activity Correlations in γ Cas

Our suspicion that the X-ray variability in γ Cas is produced near the Be star motivated us to request *Voyager 1* observations. Our request was granted, and we have obtained 1990–91 UVS data using the reduction program of Holberg & Watkins (1992) for calibration and descattering. The result is a series of 9.3Å-resolution spectra over the range $\lambda\lambda$930–1650 (except for poor sensitivity in $\lambda\lambda$1200–1360). We grouped our data into 61 useable 0.5–1 hr. bins of spectra. A temporal plot of monochromatic FUV fluxes (subset shown in Fig. 4) shows that variability over the shortest timescales we could compare binned spectra to, 0.5–2 hrs., dominates any possible longer timescale variations. These variations can exceed 0.2 mags.

To understand the nature of these rapid fluctuations we performed two analyses. First, we used all the spectra to synthesize the spectrum of the fluctuating FUV component. This was constructed at each wavelength by subtracting the flux of the third brightest spectrum from the third faintest. The result, shown in Fig. 5, is an almost white difference spectrum, except for a marginal enhancement at the Lyβ and Lyγ lines. Because this component has the same spectrum, the origin of the FUV variations is likely to be close to or even in the photosphere, not a hot site somewhere else. Second, we

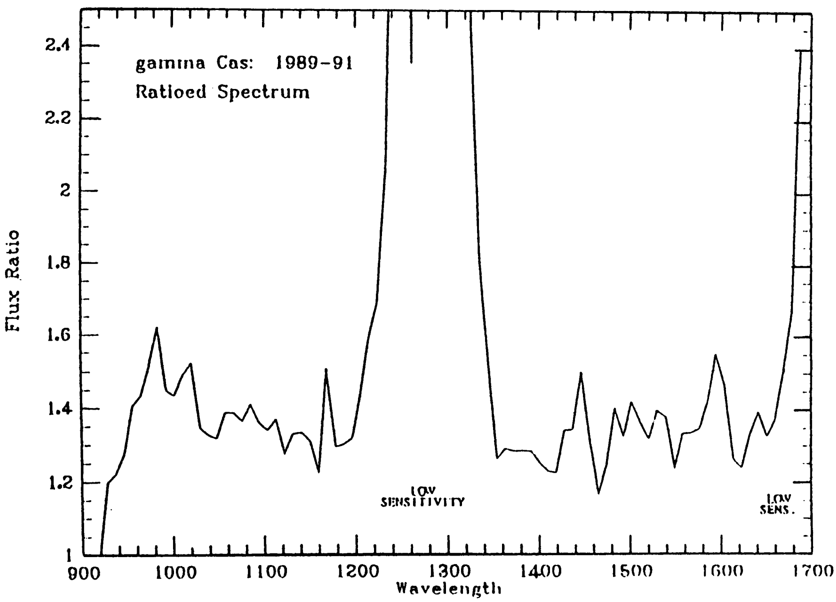

Fig. 5. Derived spectrum of FUV fluctuating component of γ Cas.

constructed a histogram of monochromatic flux differences (absolute value) between consecutive time binned observations ~1 hr. apart. This is shown in Fig. 6a. Note the flat-topped distribution out to a limit of 0.2 mags., beyond which there are few observations. This suggests that the fluctuating FUV component comes from several independent sources at any time.

To compare the FUV with the X-ray variations, we performed the same histogram analysis on the mean fluxes of consecutive orbits from the Parmar *et al.* (1993; *Exosat*; 5–9 keV) dataset in Fig. 6b and the Horaguchi *et al.* (1993; *Ginga*; 1–9 keV) data (not shown). The FUV and X-ray distributions are nearly identical in shape and magnitude threshold. Further investigation shows that the histogram form holds for data grouped even 0.5 hr apart. In view of these similarities, we suggest that the FUV and X-ray variabilities have the same origin.

What could this origin be? The energy of the fluctuating X-rays is too high for them to arise from gravitational potential energy on the surface of the Be star. The energy in the FUV component is actually about 20× that of the X-rays. This suggests that it is unlikely to originate from the steep potential well near a collapsed object either because the emitted radiation would be nearly monoenergetic. On the other hand, the three spectral characteristics we have noted, the panchromatism, dominance in the FUV,

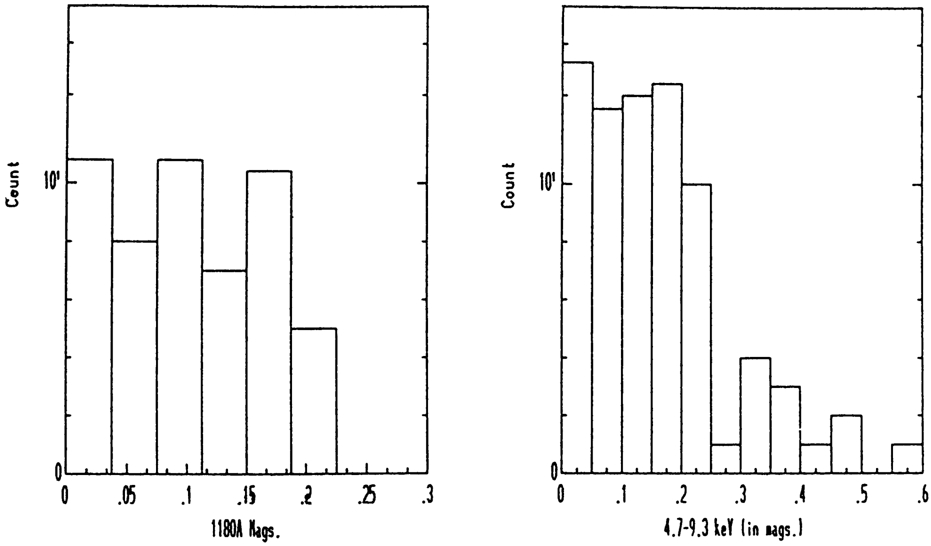

Fig. 6. Histogram comparison of rapid FUV and X-ray flux variations of γ Cas.

and possible emission in hydrogen lines are all characteristics of White Light Flares on the Sun. These flares are thought to be the reaction of the chromo-/photosphere by magnetically guided electron/ion beams, causing marginal heating of the irradiated photosphere. From the standpoint of X-ray flaring and panchromatic rapid flux variability, magnetic flaring must once again be considered as a possible mechanism. A final, important argument for the Be star origin of this activity is the observation of rapid variations along the V, R emission components (including fine structure) of the λ6678 line of γ Cas. This suggests that different sectors of the overlying plasma are excited by several transient hot sources *close* to the Be star. In our view it becomes increasingly difficult to maintain the degenerate binary hypothesis in light of these new observations.

Finally, we may turn to a number of optical photometric reports of sudden brightenings on a 1–2 day timescale in other Be stars, most recently κ CMa (Balona 1990) and ϵ Cap (Balona 1993). These reports tend to corroborate earlier visual reports of sudden, several-minute optical brightenings of HD160202 (Bakos 1970) and 66 Oph (Page & Page 1970). It would appear that magnetic flaring should be considered as the most likely single mechanism responsible for each of the aperiodic activity outlined in the foregoing (cf. Underhill & Fahey 1984).

Acknowledgements

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Discussion

Balona: Supposing your slabs are concentrated over a much wider area, or you have a grand slab covering 20–30 per cent of the stellar disk. Then you will not observe a dimple but rather a much broader line profile variation like that hypothesized for an l = 2 NRP mode. Can you comment?

Smith: Dimples have a smaller characteristic width than the global *lpv*'s from an NRP $l =$ 2 mode. It is unlikely that several slabs could "conspire" to emulate a profile shape from this mode, and far less likely still that they would do so over the many profiles that the global $l = 2$ distortion has been documented. However, it is possible at times that a few dimples could be confused with bumps from Penrod's $l = 8$ mode.

Owocki: You mentioned that dimples appear mostly at line center, but wouldn't your "slabs" also appear off disk center and thus away from line center. The one episode you did mention that appeared from line center you interpreted in terms of a falling slab, but couldn't this just be a slab off disk center?

Smith: The preference for observing dimples near line center is probably simply a signal to noise issue. On your second point, slabs can't have vertical velocities larger than the line width for the Smith-Polidan scattering mechanism to work, so they are basically doppler imaged from the disk to the profile. Thus one can discriminate between slabs having vertical velocities and their being situated near the equatorial limbs. In particular, inverse P-Cygni dimples arise from an unequal distribution of scattered photons toward the "East" and "West" edges of the penumbra. This is an indicator that the slab is moving relative to the surface.

Koubsky: Could you comment about the visibility of "dimples" in Hα profiles?

Smith: Some evidence for sympathetic dimples in Hα is presented by Smith (1989). But beyond these changes in shape, I think it may be possible for dimples to affect the line's EW. That is, if the Hα source function is high enough, incipient transient emission might be observable.

Prinja: In your slab model for λ6678 "dimples," you described a weakening of the C IV λ1550 doublet. Can you comment further on how this diagnostic relates to the slab model, and also on whether the velocity range over which profile changes in these lines is consistent?

Smith: This interpretation (see Smith & Polidan 1993) rests upon the NLTE work done by Pauldrach which suggests that when C IV lines are formed in a plasma denser than 10^{11} cm^{-3} the ratio of level departure coefficients, and hence the lines' source functions, greatly increase. This causes the C IV doublet to weaken. The slab densities we estimate are consistent with the line of sight going through plasma with this higher-than-nominal density. I found little velocity information in the IUE profiles of C IV; the variations are certainly consistent with profile changes at low velocities.

Lafon: Can your slab interpretation be considered dynamically consistent with what is known about the magnetic field of this star?

Smith: I would have to say we don't know anything about real field strengths or configurations on λ Eri. As far as dynamical model descriptions, they are still being formulated and debated even for the Sun!

Waelkens: The dimples you observe are reminiscent of those seen in β Pic, another star surrounded by a gas disk. The interpretation in that case is infall by comets. In your observations you show evidence of infall, not outflow of the "dimpling" material. Could you comment on this? Also, yesterday we learned that shocked-infall can generate X-rays. Why didn't you mention that this is a possible energy source for the λ6678 line emission?

Smith: True dimples develop in tens of minutes and show flanking emission wings. As I understand it, the β Pic features you are referring to are absorptions, only, and develop over a timescale of a day. Moreover, dimples seem to be anticorrelated with the presence of a disk or emission activity in λ Eri. I agree that infall onto the star could generate X-rays (or emission in Hα or He I lines). However, my point is that the emission that is observed is greatly in excess of what can be produced by the matter in the circumstellar disk, assuming that it were all to fall back to the star. It is the column density for the mean depth of formation of the λ6678 line which now gives us a good handle on the heating requirements, and it's too much for the CS matter available.

Kogure: I would like to ask you a question about X-ray emission from γ Cas. Murakami *et al.* showed a rapid variability of a timescale of 10 sec and attributed this to a white dwarf. Similar rapid variability was also observed with *Ginga* (Horaguchi et al. 1993). Can rapid X-ray variability originate from magnetic flaring activity?

Smith: The thesis of my talk is, yes, I think so. The chain of reasoning I make is, first, that the FUV rapid variability shows a spectral distribution like a B star's and thus can originate in the Be star's photosphere and, second, that the FUV and X-ray show similar temporal characteristics. Taken together, these facts suggest that the X-ray variability originates there too. I suggest a picture like that of solar White Light Flares, which appear to originate from particularly energetic beams of electrons or ions induced by flares. These penetrate deep into the Sun's chromosphere or photosphere where they can elevate the temperature of high density plasma only slightly. As for the timescale of the X-ray variations, they show chaotic behavior, which means there is no characteristic timescale over a range from $\sim$10 sec to $\geq$90 minutes, perhaps longer. The neutron star advocates have attempted to use 10 sec as a diagnostic for infall into a n.s. potential well, but this is not correct if there is no special timescale. The white dwarf picture has the problem of requiring a rather high mass loss rate. I think that each of these pictures suffers from these problems, though they probably can't be ruled out.