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DYNAMIC PROCESSES IN Be STAR ATMOSPHERES. IV. COMMON ATTRIBUTES OF LINE PROFILE "DIMPLES"

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ABSTRACT

"Dimples" are transient central absorption features flanked by weak emissions commonly seen in the He I λ6678 line profile of the mild B2e star λ Eridani. Smith & Polidan have found that these features can be reproduced with a model in which line photons are scattered within an optically thick (in the line) slab elevated over the surface of a rapidly rotating star. We have undertaken a series of simultaneous He I multiline observations of this star at the McMath, McDonald, Lick, David Dunlap, and Ritter Observatories to search for dimples in weak blue He I lines when they appear in λ6678. Four dimples were found during 15 hr of multiobservatory monitoring. In three cases, a dimple was observed in a weak blue line of the same absorption series as λ6678. In the fourth instance, a dimple was observed only in λ5876 and λ5015 lines that, like λ6678, are strong and have weak wings. A joint *IUE*/optical campaign demonstrated that the He II λ1640 line shows decreases in absorption and possible weak emissions just as new dimples appear in the λ6678 line.

Our observations confirm a previous report that dimples appear in the λ6678 line of four other Be stars. We also find that the resonance C IV double weakens when dimples appear, a result similar to that found for λ Eri. Our data also disclosed that "migrating subfeatures" similar to those found in γ Cas are present in the λ6678 line of the B5 star HR 1011. These features appear to be a more vigorous form of dimple activity than observed in λ Eri and other mild Be stars. These findings lend support to the slab model as an explanation for the dimple phenomenon. They also suggest that this activity is endemic to the class of mild Be stars. The appearance of dimples in the weak blue He I lines suggests slab masses of at least 7×10^{-13} $M_\odot$ for most dimples.

The greatest enigma that characterizes classical Be stars is their highly variable and episodic mass-loss histories. Our estimates of dimple-slab masses are high enough that this problem may be removed if the magnetic paradigm for Be activity is correct. In this picture, exospheric flares trigger explosive ablations of plasma from the upper photosphere. The evaporated mass is trapped by overlying closed magnetic field loops, where it cools, taking on characteristics of prominence-like structures. If the loops were opened for any reason, this mass would be free to escape from the star at a rate consistent with mass-loss rates during active Be episodes. Then the essential difference between Be stars in active and inactive phases would be understood not as a difference in their mass release rates but rather in the prevailing geometries of their surface fields.

Subject headings: line: profiles — stars: emission-line, Be — stars: flare — ultraviolet: stars

1. INTRODUCTION

The B2e star λ Eridani has become one of the most intensively studied classical Be stars because of the practical ease of observing its photosphere unobscured by circumstellar obscuration and because of its ubiquitous multiwavelength variability, including an X-ray flare (Smith et al. 1993). The star displays Hα emission and nonemission phases that alternate at unpredictable intervals every several months to a year. The star λ Eri also shows a rapid variability that includes periodic light and line profile modulations every 0.71 days (Bolton & Stefl 1990; Smith 1989), generally attributable to nonradial pulsations (but see Baade & Balona 1994), and a chaotic component with timescales ranging from minutes to days. The star's strong He I λ6678 line has been the target of several campaigns over the last decade. One of the greatest surprises of these efforts has been the realization that the chaotic variation tends to be more prevalent during the nonemission phases, a circumstance probably resulting from the photosphere often being clearly visible. Two of the most common types of variability in the He I λ6678 line are brief "microemissions" and "dimples." Dimples were studied extensively by Smith & Polidan (1993, hereafter SP93). These authors define this phenomenon exclusively for the λ6678 line of λ Eri as "the unexpected appearance of central 2–3 Å wide cusp-shaped absorption flanked by incipient emission. The emissions and absorptions cancel so that the line strength ... remains constant to within measurement errors ... of the distorted profile."

Dimples typically appear at irregular times, last for 2–4 hr, and are most easily observed near the center of the line. Two or more of them may appear or coexist at the same time. These features travel from blue to red across the line profile, but their short lifetimes generally do not permit a comparison of their motions with the estimated rotational acceleration rate.

SP93 used geometric arguments and Doppler mapping models to simulate dimples on integrated flux profiles. They

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postulated that a dimple forms from an optically thick (in the line) stationary slablike structure above the photosphere. Line photons rising from the photosphere scatter off the bottom edge of the slab toward the direction of the local horizon. They are absorbed along the optically thick paths toward the horizon and scatter a second time. In doing so, they acquire a Doppler shift in the frame of the external observer. As a consequence, photons that are removed at an initial wavelength are redistributed into neighboring velocities, giving the integrated flux profile a characteristic dimple shape. SP93 noted that dimples are sometimes observed with more emission in one dimple wing than the other. Such "P Cygni–shaped" features can be understood if the slab has a small ($\sim$40 km s^{-1}) vertical and moderate transverse velocity component. The SP93 models indicate that the slab condensations responsible for dimples lie 0.1–0.2R_* above the star and have an area 2%–4% of the star's projected disk. Non-LTE TLUSTY model atmospheres (Hubeny 1988) were used to estimate densities of 10^{11}–10^{12} cm^{-3}. Although these numbers are self-consistent, we note that the SP93 picture was constructed only from a three-dimensional geometrical model. The line scattering assumptions have not yet been explicitly confirmed.

We should mention that there is no evidence that the periodic line profile variations of λ Eri are related to the appearance of dimples. For example, the latter appear at erratic intervals. We take the point of view that the current controversy over nonradial pulsations (which we favor) versus rotational modulation (e.g., Baade & Balona 1994) in Be stars like λ Eri is largely irrelevant to the formation of these features, in part for this reason. Moreover, the velocities implied from the appearance of dimples (see below) are more than 2 orders of magnitude larger than amplitudes of nonradial pulsation waves that may be present, even if several modes were present and occasionally interfered constructively. As in Smith (1989), we believe that the passage of pulsational waves may *at most* be a triggering mechanism for specific transient events in line profiles but that they are probably not caused or energized by the pulsations. Note that no bona fide model has ever been presented to explain how small amplitude pulsations could either grow or eject mass at the rate required for Be stars, or to explain the episodic nature of these Hα- and wind-active phases.

If dimples were found to be present in other lines and in the spectra of other Be stars, they could conceivably provide an understanding of the instability mechanism responsible for mass-loss episodes (the "Be phenomenon"). It is important to rule out mechanisms that somehow might produce dimples from conditions unique to the circumstellar environment of only λ Eri and affecting only the λ6678 line. Thus, it becomes crucial to monitor these features in other Be stars. It is also of interest to observe them in weaker He I lines at the same time they appear in the λ6678 line, because weaker lines permit a closer estimate of total column densities in optically thick slabs.

For these reasons, we have mounted a series of campaigns on λ Eri to observe two or more of its He I lines simultaneously. The solar-stellar spectrograph on the McMath-Pierce solar telescope (Kitt Peak) was used, together with a second telescope at Ritter (Toledo), Dave Dunlap (Toronto), McDonald (Texas), or Lick Observatories. We were also awarded time with the *International Ultraviolet Explorer* (*IUE*) satellite to compare the behavior of the C IV resonance and He II Balmer-alpha line. Because the scattering mechanism explored by SP93 requires a Doppler remapping of line flux on a rapidly rotating star's surface, dimples should be common features in line profiles of other mild classical Be stars.[5] To follow this expectation, we monitored a few other Be stars with $V \sin i$'s comparable to λ Eri's ($\approx$310 km s^{-1}). The ubiquity of dimples in various lines in λ Eri and other Be stars and the large amount of mass contained in dimple slabs implied from these results suggest that they are intimately related to the general circumstellar activity of classical Be stars during both their Hα emission and nonemission phases.

2. OBSERVATIONS

A series of four campaigns was carried out to investigate the response of other optical and UV lines to dimples in the λ6678 line. The first was a collaboration among observers at the McDonald 2.1 m and McMath 1.5 m telescopes on 1992 January 5, the second at the McMath, Ritter (University of Toledo 1.2 m; echelle), Lick (3 m; echelle), and David Dunlap (University of Toronto 1.9 m; echelle) Observatories in 1993 October. All of these instruments gave a spectroscopic resolution between 40,000 and 50,000, except for the Ritter instrument, which provided a resolution of 28,000. The McDonald 82 inch (2.1 m) coudé used a RL1872H Reticon with 15 μm pixel and provided a sampling of 57 μm pixel^{-1}. No fringing was noticed in these data, although some instabilities in the continuum were particularly noticeable at the edges of the spectral field. These flaws did not seem to affect the rectification of the continuum near the λ4388 line. The Ritter observations were performed with a Wright Instruments 800 $\times$ 1200 chip with 22.5 μm pixel. Our configuration provided a sampling of 0.032 Å pixel^{-1}. Among all our data sets, only the DDO observations (0.038 Å pixel^{-1}) showed some fringing, but only on October 24 and early in the evening of October 26. No other instrumental anomalies were in evidence. Typical exposure times on these instruments were as follows: McMath, 6–12 minutes; McDonald, 15 minutes; Lick, 20 minutes; DDO, 20–30 minutes; and Ritter, 40 minutes. The dates, lines, and times of simultaneous coverage in these two campaigns are shown in Table 1.

The Lick entry refers to the λ6678, λ5015, λ4922, λ4471, λ4388, and Hα lines. Only portions of the λ5876 profile were visible on October 29 because of contamination by telluric water vapor features. All our optical data were reduced and analyzed with standard IRAF ONEDSPEC and TWODSPEC packages.

The third campaign consisted of processings of *IUE* data both with IUESIPS software and with a prototype version of "NEWSIPS" software; NEWSIPS has recently been adopted as the *IUE* processing standard. These reprocessings were done for a series of archival images obtained on three "US2" shifts on 1990 October 21–23 (24 hr total) previously discussed by SP93. SP93 found that the C IV and N V doublets weakened by $\approx$10% when eight out of nine dimples appeared in the λ6678 profile. The noise in the strengths of the He II λ1640 line did not permit conclusions to be made about this line's response to dimples. Because the signal-to-noise ratio in NEWSIPS relative to IUESIPS

[5] They are putatively single Be stars that do not show Hα or He I line emission most of the time.

TABLE 1

LOG OF λ ERI OBSERVING CAMPAIGNS OF He I LINES

Date	McMath Line	Alternate Site	Line	Alternate Site	Line	Common Coverage (hr)
1992 Jan 5	6678	McDonald	4388			1.5
1993 Oct 24......	6678	DDO	4388, 4471	Ritter	4388	1; 3.5
1993 Oct 25......	6678	DDO	4388, 4471	Ritter	4388	3; 3.5
1993 Oct 26......	6678	DDO	4388, 4471	Ritter	4388	3.5
1993 Oct 29......	6678	Lick	All[a]			3

[a] The Lick entry refers to the λ6678, λ5015, λ4922, λ4471, λ4388, and Hα lines.

processings is ~2 times higher for high-dispersion SWP spectra (Smith 1994), we extracted the He II λ1640 lines from both processings to see if dimples in He I lines cause a response in this important feature.

Our fourth campaign again included the McMath and the *IUE*. We targeted four mild Be analogs of λ Eri noted by SP93 that have shown evidence of dimples in λ6678 (SP93; see their Table 2). This campaign was carried out with the McMath and the *IUE* satellite in 1993 November. The purpose of the *IUE* observations was to test the SP93 result that, when dimples appear, the C IV resonance lines weaken. The McMath solar-stellar spectrograph (TI4 CCD) was again used for the λ6678 line. To increase our efficiency, we divided our sample into two pairs of stars and observed each pair alternately on two nights. During each *IUE* shift, 5–6 UV spectra and 10–15 optical spectra were obtained from each star. *IUE* time constraints prevented us from observing a fifth star, so we dropped the dimple candidate 120 Tau. This turned out to be an unfortunate choice because the C IV lines of HR 1011 turned out to be too weak to detect variations.

Observations of the three campaigns on λ Eri were carried out at times when the Hα line and the optical He I lines showed no violet/red wing emissions from a circumstellar disk. Although Be stars in nonemission phases are often thought to be inactive, close examination of the λ6678 line often shows erratic variability (Smith 1989). The most common forms of this are fluttering microemissions and dimples. Both these patterns evolve on similar timescales, and it can be difficult at times to separate the two from one another. Generally, dimples conserve the line's equivalent width, whereas emissions, of course, fill in the line. Yet this is not a foolproof test in all cases. In a companion paper (Smith et al. 1997), we find that true emissions in the λ6678 line are equally visible in λ5876 but barely detectable in the blue He I lines. On the other hand, anticipating our results below, dimples *usually* may be seen clearly in the latter group. The λ5015 line exhibits the greatest contrast by showing strong dimples and weak emissions.

3. RESULTS

3.1. *Multiline Search for Dimples in λ Eri*

Figure 1 records the simultaneous appearance of a dimple in λ6678 and λ4388 observations obtained at the McMath and McDonald facilities. On this particular night, we had bad weather at Kitt Peak and hence little common time coverage. Nonetheless, the activity in both lines proceeded rapidly during this time. For example, the λ6678 profile shown, the first McMath observation of the night, shows a clear dimple. The λ4388 shows a corresponding feature, but none was visible in a spectrum obtained 16 minutes earlier. This dimple weakened over the next hour in both lines. The equivalent widths for both lines were conserved to within measurement errors, making the dimple classification straightforward.

We have found two other examples of the blue-green lines responding to dimples. Figure 2*a* records the simultaneous appearance of a dimple in the λ6678 (McMath) and λ4388 (DDO) lines. Figure 2*b* shows a similar response to a dimple in the λ4388 line from Ritter data. The observation of dimples in these weak blue He I lines indicates that the exospheric structures producing them are optically thick in these wavelengths as well as in λ6678.

These examples do not mean that all dimple events are necessarily visible in the blue He I lines. In one instance, depicted in Figure 3*a*, a dimple appeared in λ5015 and λ6678, and probably even in λ5876, but not in the next two series members, λ4922 and λ4388, nor in the triplet λ4471 line. In addition, Figure 3*b* shows that, for the dimple shown in Figure 2*a*, the λ4471 profile has a possible weak emission where an absorption would be expected.

The above observations are the first to illustrate the response of several lines to the apparition of a dimple in the reference λ6678 line of a Be star. They tell us clearly that the original definition of dimples for the λ6678 line in λ Eri's spectrum should be broadened. Moreover, we see that, if a dimple is to appear in the blue lines, it will do so within minutes of its appearance in λ6678. The SP93 model for dimples requires that a slab above the photosphere must be optically thick. The goal of our analysis is to estimate an actual column density for a dimple slab rather than merely giving a lower limit. To facilitate a comparison of the observed He I lines, we have used TLUSTY atmospheres to estimate line strengths, $N_{r,s}\,gf$ at the reference depth where the λ6678 line core is formed. These are shown in Table 2. For members of the same absorption series, the entries follow the ratios of the atomic *gf*-values. We selected three model atmospheres having $T_{\rm eff}$ = 16,000, 24,000, and 50,000 K (log g = 4.0). The first model is an arbitrarily cool one that is needed to bracket likely conditions, the second is our reference $T_{\rm eff}$ for λ Eri, and the third is a representative model for which λ6678 emission can be produced at high atmospheric layers (Smith et al. 1994b).

For the three cases exhibited in Figures 1 and 2, the visibility of dimples in λ4388 increases the estimated column density by the ratio of the *gf*-values (15 times) beyond the estimate of 2.5×10^{-3} g cm^{-2} that SP93 were able to estimate from the dimples' presence in λ6678 alone. However, it is actually the fourth dimple we observed (Table 2) that provides an actual estimate, rather a limit, of the slab column density. This surprising result comes from the feature being observed in λ5015 during the brief interval in which it first becomes visible as only a sharp absorption core. SP93 pointed out that a sharp core is the signature of

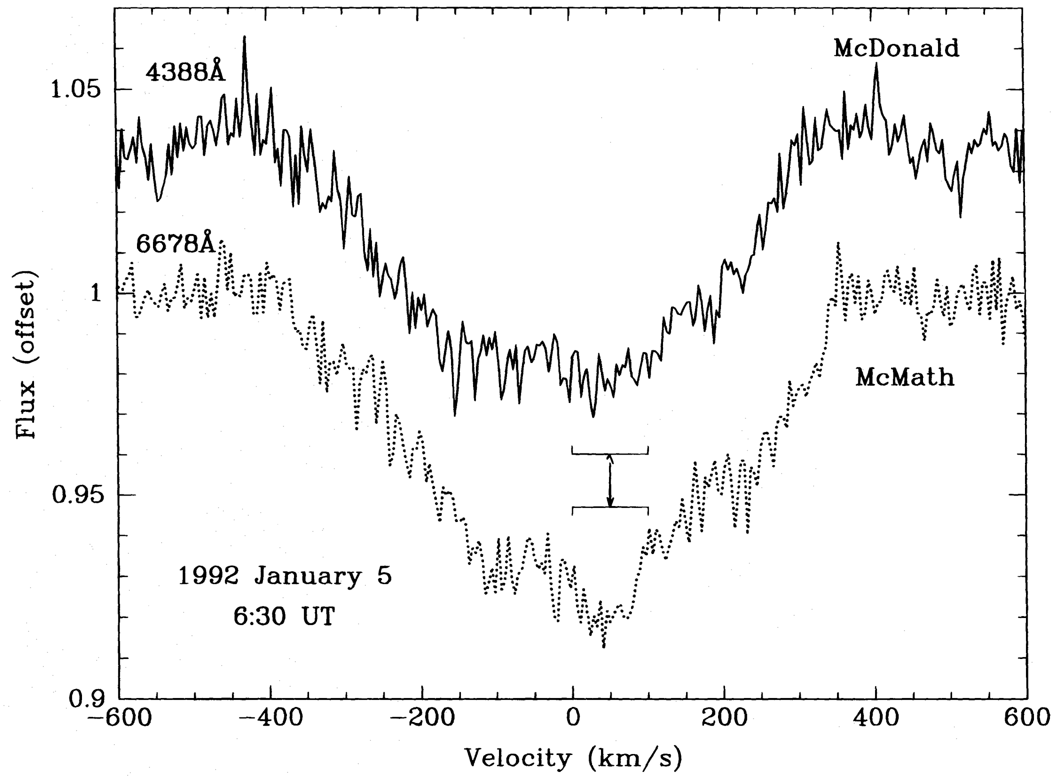

FIG. 1.—A "dimple" simultaneously observed in the He I line profiles of the $\lambda6678$ and $\lambda4388$ lines at different observatories. The two profiles are offset in intensity for convenience. The central absorption component (*arrow*) as well as the flanking faint emissions are especially discernible in the $\lambda6678$ line. Both these transitions arise from the 2^1P level.

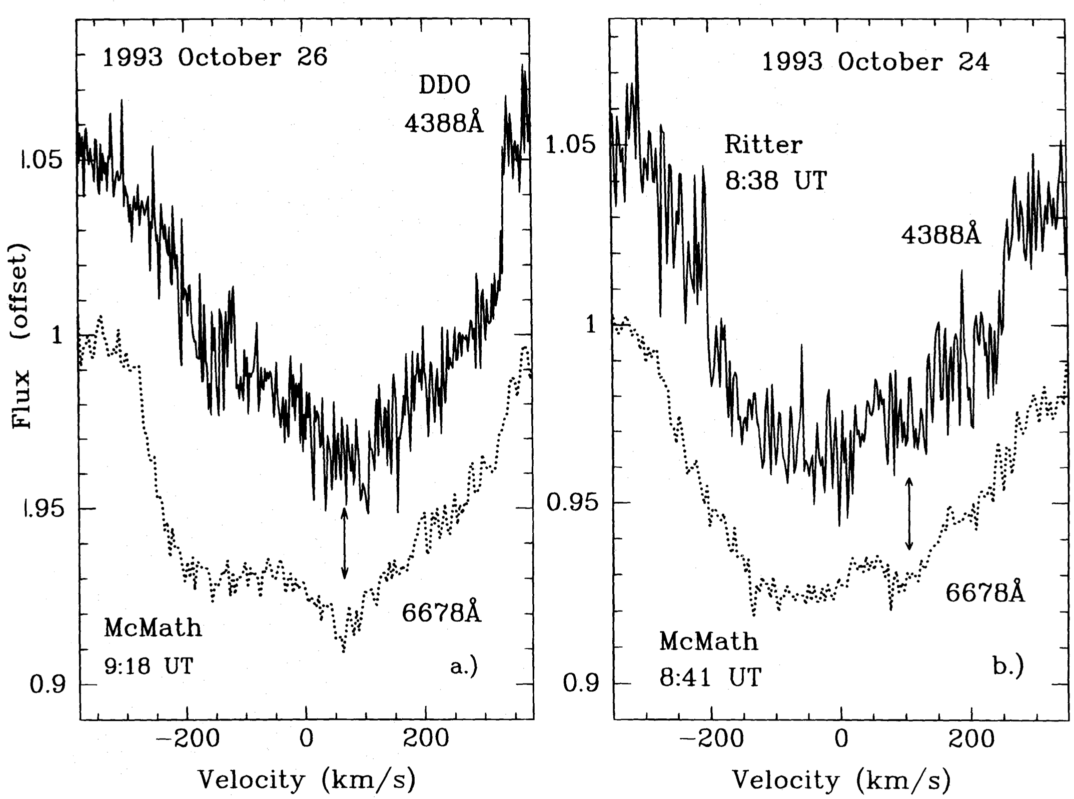

FIG. 2.—Two dimples captured in the $\lambda4388$ line at alternate observatories as well as in the $\lambda6678$ line at the McMath site. In addition to the dimple denoted by the arrow in (*b*), another dimple may be present at $\sim +200$ km s^{-1}.

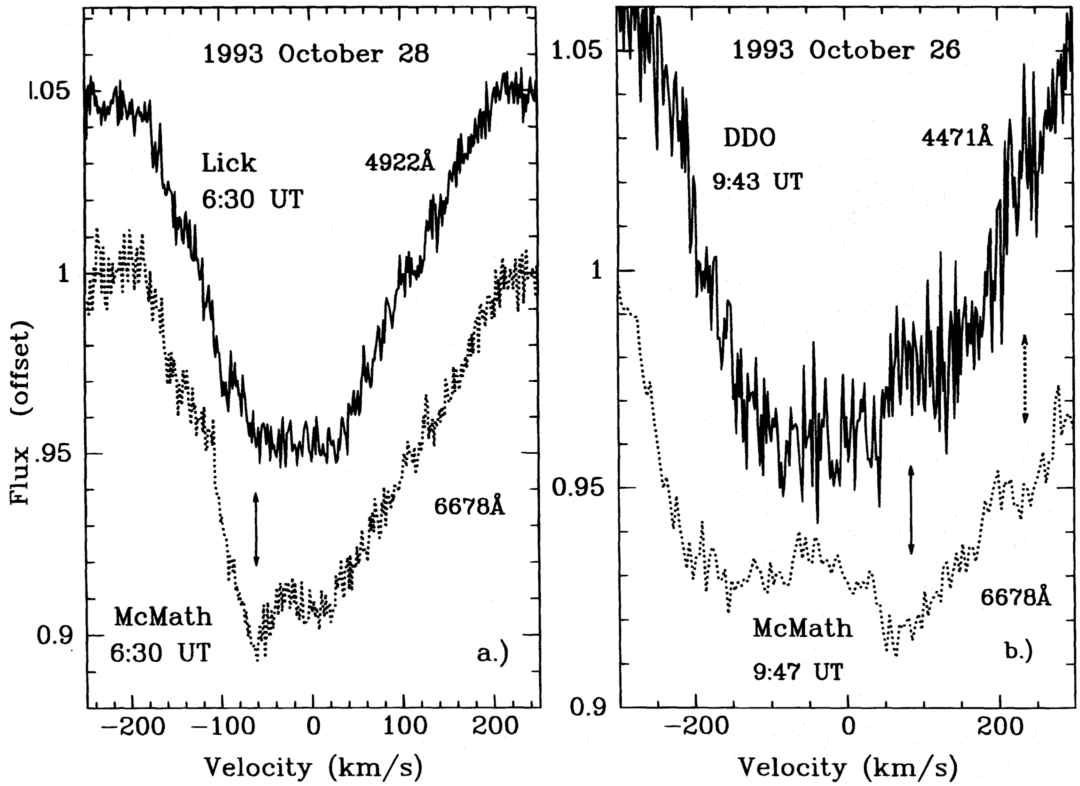

FIG. 3.—(*a*) An example of a dimple appearing in the λ6678 line but not in λ4922, which is the next transition series member; (*b*) an example of the triplet λ4471 showing a rather different response to a dimple in λ6678. Note that the former shows emission at the position of the dimple absorption.

a developing dimple just becoming optically thick. By interpreting this feature as $\tau_{5015} = 1$, one can scale the results of SP93 by the entries in Table 2 to derive a column density of 7×10^{-2} g cm^{-2} and a total slab mass (assuming $R_{\rm slab} = 1$ $R_\odot$) of 7×10^{-13} $M_\odot$ for our weak dimple. One may also come at the slab mass problem from the other direction. By noting that dimples seem to be undetectable in broadband photometry, one can estimate an *upper mass limit* for slabs. For example, from ground-based (e.g., Wasatonic 1994) and ultraviolet flux monitoring with the *IUE* satellite (SP93), we believe we can set an upper limit to short-term flickering of 0.003 mag over a timescale of 1 hr or so. This limit would imply τ(cont) ≤ 0.1 and a slab mass of $\leq 3 \times 10^{-11}$ $M_\odot$. This value is too high to be a realistic estimate of a slab's mass, but it does show that there is no conflict between the appearance of dimples in spectral lines and their invisibility in broadband photometry.

A mass of 7×10^{-13} $M_\odot$ for weak dimple slabs should be sufficient to produce observable Hα emissions (Marlborough 1995). In principle, careful monitoring could even betray a flickering of Hα emission as slabs emerge and disappear behind the limb with stellar rotation. Smith (1989) noted that dimples can be observed in λ Eri's Hα profile. A particularly important consideration is the total amount of material contained by dimple slabs everywhere over the star's surface. We estimate that approximately three slabs exist over the star at any time. Then the revised mass estimate above implies that some 2×10^{-12} $M_\odot$ must be tied up in them. This is comparable to the mass detectable from Hα emission in the weakest observable disks around this star (e.g., Smith, Peters, & Grady 1991; Marlborough 1995). Thus, it is misleading to think of λ Eri as "inactive" just because its Hα line does not show prominent emission.

One remaining consideration from Table 2 is the breakdown in perfect correspondence between dimple visibility and line strength among the He I lines. The dimple of October 29 was not observable in the λ4922, λ4388, and λ4471 lines, even though their line strengths are larger than the λ5015 line. This breakdown implies that a line strength

TABLE 2

RELATIVE LINE STRENGTHS[a] FOR SAMPLE MODEL ATMOSPHERES

Line	Lower Term	$N_{r,s}gf$(at $T_{\rm eff}$) 16,000 K	24,000 K	50,000 K	1993 October 29 Dimple?
λ5015......	2^1S	0.57	0.33	0.20	Yes
λ6678......	2^1P	13.2	10.2	5.8	Yes
λ4922......	2^1P	2.2	1.7	1.0	No
λ4388......	2^1P	0.81	0.63	0.36	No
λ5876......	2^3P	125	77	79	Yes
λ4471......	2^3P	25.6	15.7	16.0	No

[a] g mm^{-3}.

alone cannot be the whole story for making a dimple visible. Moreover, the departures of the atomic level populations from their LTE values are known to be all rather similar (Smith et al. 1994b). A more likely cause for the difference in dimple visibility is that the Stark broadenings in the wings of He I lines are much stronger in the $n \geq 4$ members of the diffuse (2^1P–n^1D and 2^3P–n^3D) series than for the principal series members λ5876, λ6678, and λ5015 (Barnard, Cooper, & Smith 1974; Mihalas et al. 1975; Heasley & Wolff 1981; Wolff & Heasley 1985). The damping wings and forbidden components permit alternate routes for depopulation of the upper levels of the $n = 4$ transitions through collisional excitations. These alternatives discourage dimple formation. These considerations push the dimple masses from the diffuse lines to higher values than $6 \times 10^{-13}\,M_\odot$.

3.2. *Response of* He II λ1640 *to Dimples*

Figures 4–6 display the equivalent widths of λ1640 for three *IUE* US2 shifts on 1990 October 21–23. We estimated error bars for these measurements in two ways, and they showed good agreement with each other. First, we measured equivalent widths in IRAF by allowing spline and Chebyshev functions to determine the most different reasonable continua and by comparing the inferred total absorptions. Second, we mapped several λ1640 line profiles into the Fourier domain, estimated the noise from the white noise at high frequencies, and applied this error to the transform at zero frequency. The resulting error bars for both NEWSIPS and IUESIPS (Fig. 6) are indicated. In each of these figures, a mean equivalent width of 0.55 Å is shown as nominal for λ Eri's Hα-nonemission state. This is close to the value determined from the 1987 November data (Smith et al. 1997). Our interest here is in the several significant decreases, often for hours at a time, that coincide with optical line dimples.

The lower panel of each of these figures shows the first profile in a series in which a new dimple just becomes visible. A comparison of the times of λ6678 dimple appearances and decreases in λ1640 line strength shows an excellent correspondence. Moreover, significant fluctuations in the λ1640 line strength are always in the same sense and arise more or less simultaneously with weakenings of the C IV and N V doublet (SP93). This correspondence tightens up further in the C IV line data processed with NEWSIPS. One exception to this statement is the appearance of a dimple at 10 UT on 1990 October 22, which does not show a λ1640 weakening (although it can be seen in the C IV data; SP93).

On a few occasions, such as 11–12 UT October 21 and 11 UT October 22, the decreases in λ1640 line strength are particularly sharp. One can compare these decreases with the effect of a removal of line absorption in a rapidly expanding area on the star's surface. Such a hypothetical event would describe a $(r/R)^2$ trajectory in our plots. These trajectories are shown as dotted parabolae in Figures 4 and 5 for an expansion velocity of 800 km s^{-1} (the surface escape velocity) and for $R_* = 6\,R_\odot$. Whenever the line weakenings are found to fall off more sharply than this

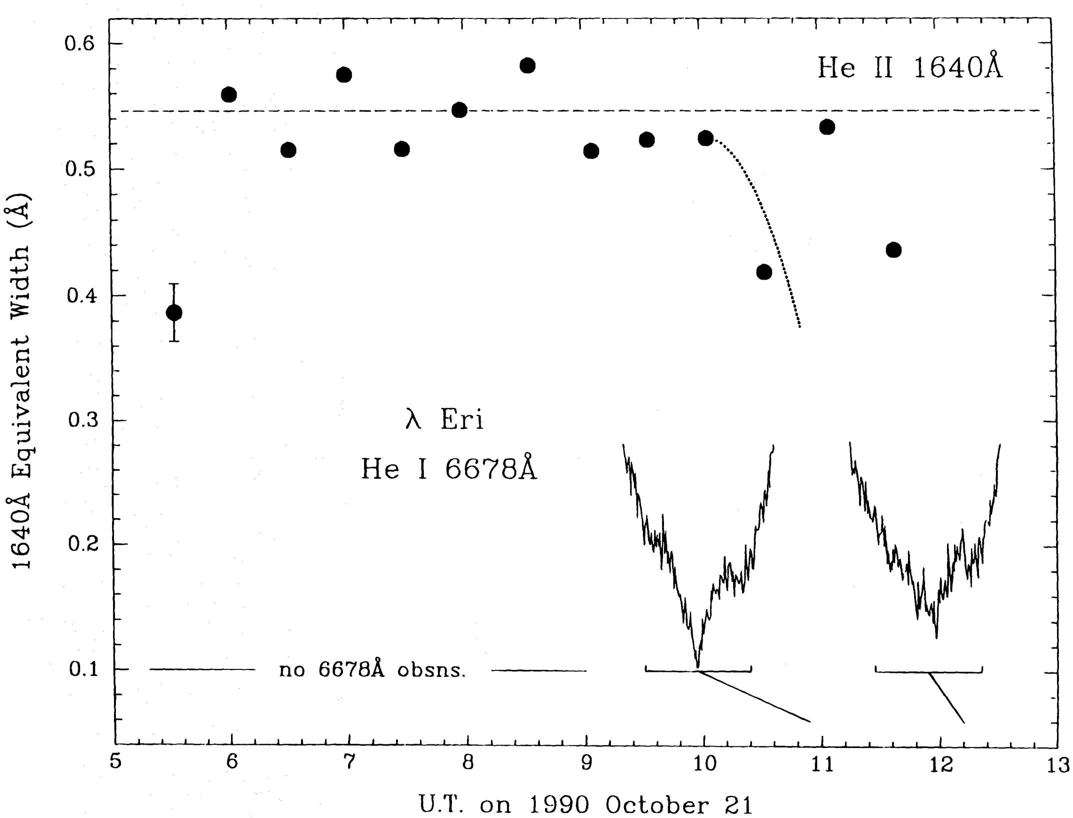

FIG. 4.—A comparison of the He II λ1640 line strength measured with NEWSIPS processings and optical observations of the He I λ6678 profile (core only) when two dimples first appeared on 1990 October 21. The dashed line denotes the average quiescent period strength of λ1640 during three nights of observations. NEWSIPS data show λ1640 weakenings when a dimple appears. Note the revival of a second dimple at the red edge of the core at 12:11 UT following the partial recovery from a dimple an hour earlier. The dotted parabola describes the effect of a hypothetical disturbance on the star's surface. Because this trajectory falls above the observation at 10:32 UT, the equivalent width decrease at this time must be caused by a true emission process in the line.

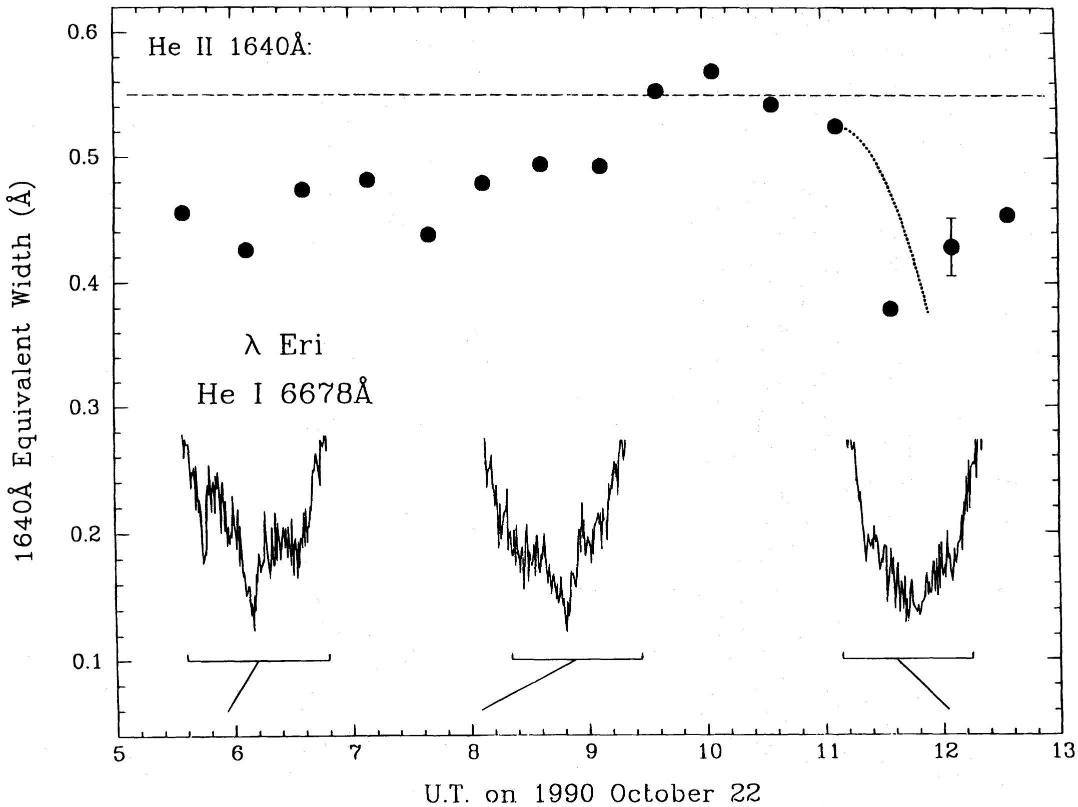

FIG. 5.—A comparison of the λ1640 line strength measured with NEWSIPS processings and optical observations of the λ6678 profile (core only) when two dimples first appeared on 1990 October 22. The dotted parabolic trajectory again shows that the equivalent width decrease for the observation at 11:35 UT must be caused by a true emission process in the line.

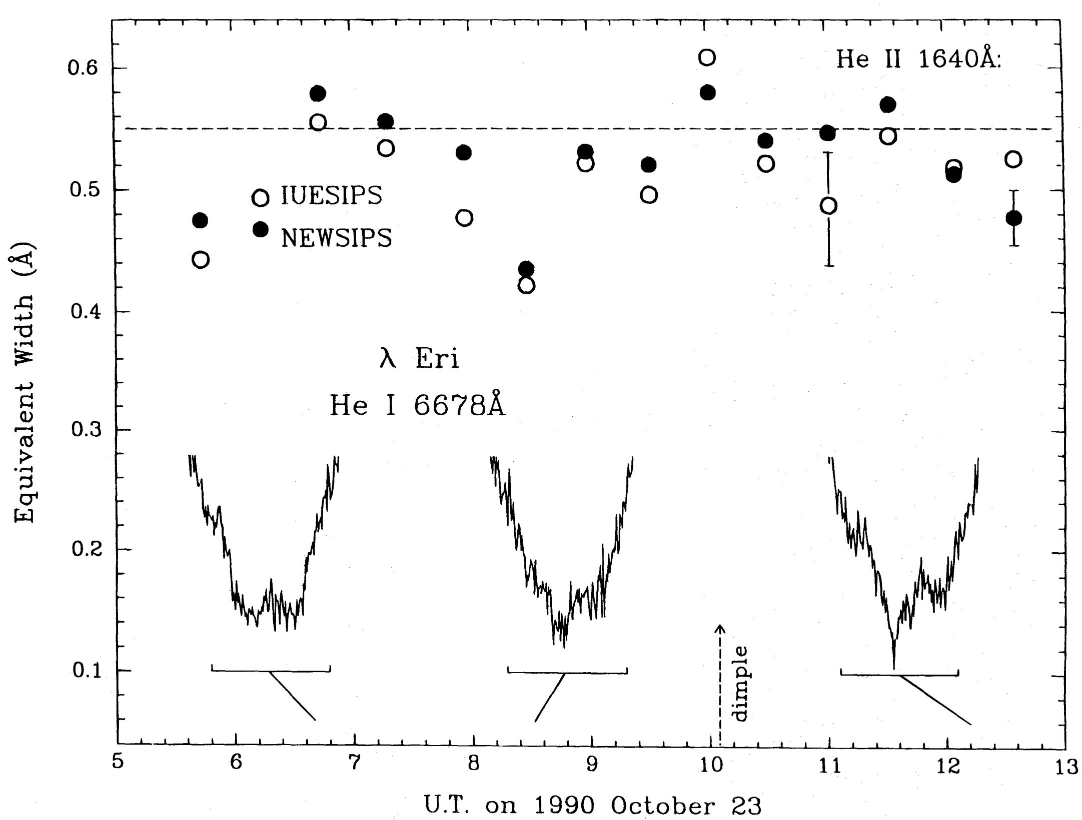

FIG. 6.—A comparison of the λ1640 line strength measured with both IUESIPS and NEWSIPS processings and optical observations (core only) of the λ6678 profile when two dimples first appeared on 1990 October 23. The errors for NEWSIPS data are only half the errors for IUESIPS. The arrow shows the only dimple that appeared during three nights of monitoring that was not accompanied by a weakening of λ1640.

locus, the local line profile intensity emitted from the disturbed area must necessarily be greater than the continuum value and/or due to emission from material viewed over the limb. We do not feel that we can discriminate between these possibilities for just a few cases. If the former should be true, then the recombination of He II from He III would be implied. If He II is emitted beyond the stellar limb, it would imply that the volume of ejected material is actually much larger in this line than inferred from the optical He I lines.

3.3. *Line λ6678 Dimples in Other Mild Be Stars*

As part of a general survey of He I λ6678 and λ4922 line strengths in B0–B5 stars (Smith, Hubeny, & Lanz 1994a), we devoted a night of McMath time in 1991 to observing several mild Be stars. A sampling of two to five spectra was sufficient to find temporary dimple-shaped features in five stars. Figure 7 exhibits the discovery observations for each of these dimples. These initial observations are insufficient to prove that dimples appear in these stars' λ6678 line profiles. For one thing, irregular transient emissions on different parts of the profile can occasionally produce shapes similar to dimples. Accordingly, an observation strategy of observing each star on two nights was set up to ensure that we could distinguish between stable and temporarily distorted profile shapes.

Figures 8 and 9 record dimples in the λ6678 lines of the B2e stars 8 Lac and 56 Eri. We have used difference profiles in these illustrations to bring out the contrast of these faint dimples—four and two, respectively. In the differencing format, a dimple ideally shows a central absorption with flanking weak emissions above the zero "continuum." Figure 9 shows that the emissions for 56 Eri are particularly noticeable. Our plots also indicate the measured equivalent width of the C IV λ1548 line. An arrow indicates the observation closest to the optical observation shown. In virtually all cases, the appearance of a dimple coincides with a weakening in the C IV line. We also observed (not shown) a 9% weakening in the strength of λ6678 for HR 1423 at ~10 UT on 93 November 5, just when a dimple was observed in the He I line.

Figure 10 shows the blue-to-red progression of what at first appears to be a pair of separated dimples in several differenced λ6678 profiles of the B5 star HR 1011. However, these features show two differences from the usual dimple behavior in λ Eri: (1) long lifetimes of several hours marked by rapidly fading in and out of visibility and by changes in shape, and (2) a ~300 km s^{-1} separation of pairs of absorptions or emissions within a pattern. These characteristics are remarkably similar to the migrating subfeatures found by several observers in several lines of γ Cas (Yang, Ninkov, & Walker 1988; Horaguchi et al. 1994; Smith 1995). As is also true for γ Cas (Smith 1995), the migration rate is consistent with the rotational advection rate for standard stellar parameters (sin $i \approx 1$, $R_* \approx 5\ R_\odot$, and $V \sin i \approx 245$ km s^{-1}; Uesugi & Fukuda 1982). Figure 10 indicates the disappearance and reemergence of the subfeature pattern in the middle of our time series. The reemergence first appears in a "precursor" analogous to that noted by Smith (1995) for γ Cas. These observations badly need a more extensive follow-up. Nonetheless, it is clear that these microfeatures are very similar to those observed in the time series of γ Cas. This discovery removes γ Cas from its unique status of exhibiting ubiquitous migrating subfeatures. Ironically, it is removed by a star not classified as a Be star.

Smith (1995) concluded that these subfeatures arise from an organized velocity field with an amplitude well in excess of the local sound speed over the surface of γ Cas. The argument he used, the phenomenological behavior of lines

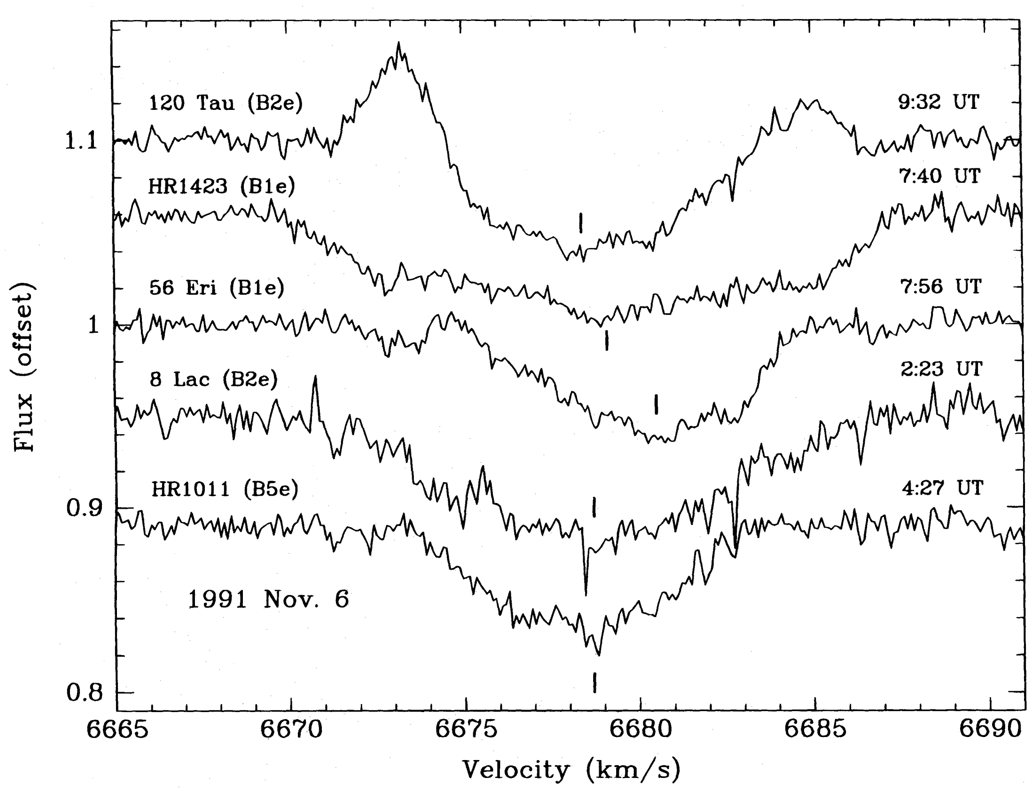

FIG. 7.—A summary of discovery observations of dimples in the λ6678 line of five mild Be stars (McMath observations)

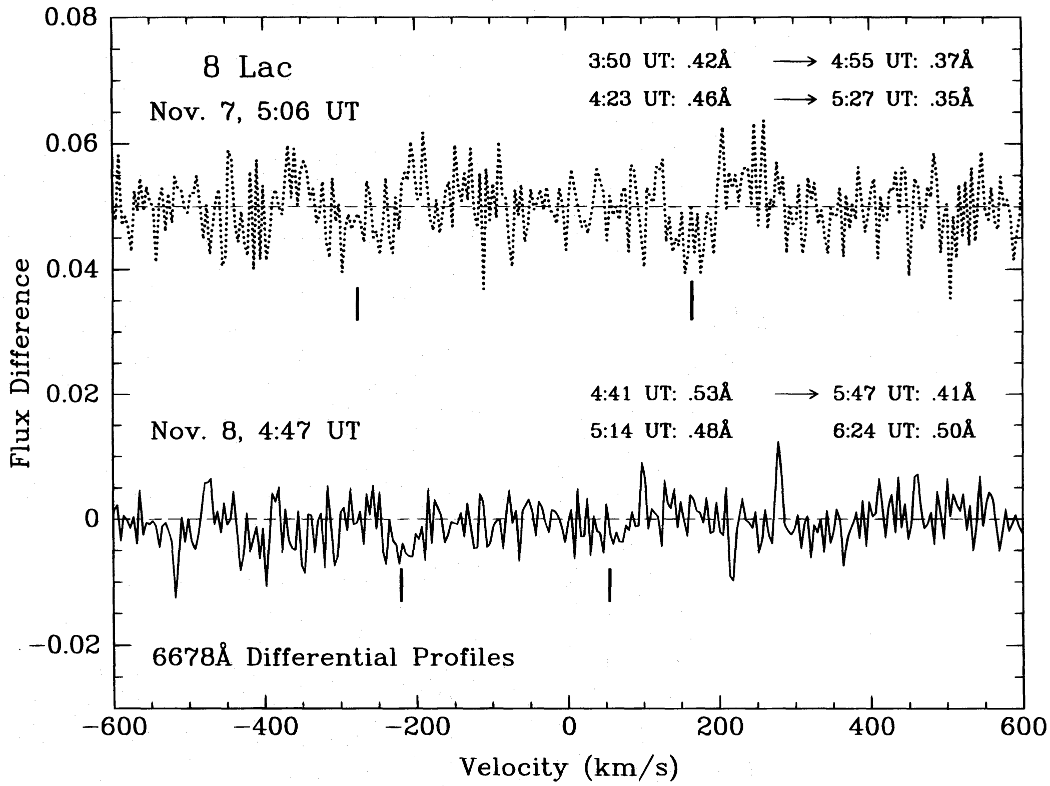

FIG. 8.—Difference profiles of a sequence of $\lambda6678$ line profiles for the mild B2e star 8 Lac on two nights showing subtle absorption and emission features (*heavy lines*). The times of the *IUE* observations and the equivalent widths of the C IV $\lambda1548$ line are indicated, showing a weakening at approximately the time an $\lambda6678$ line dimple is observed (*arrow*).

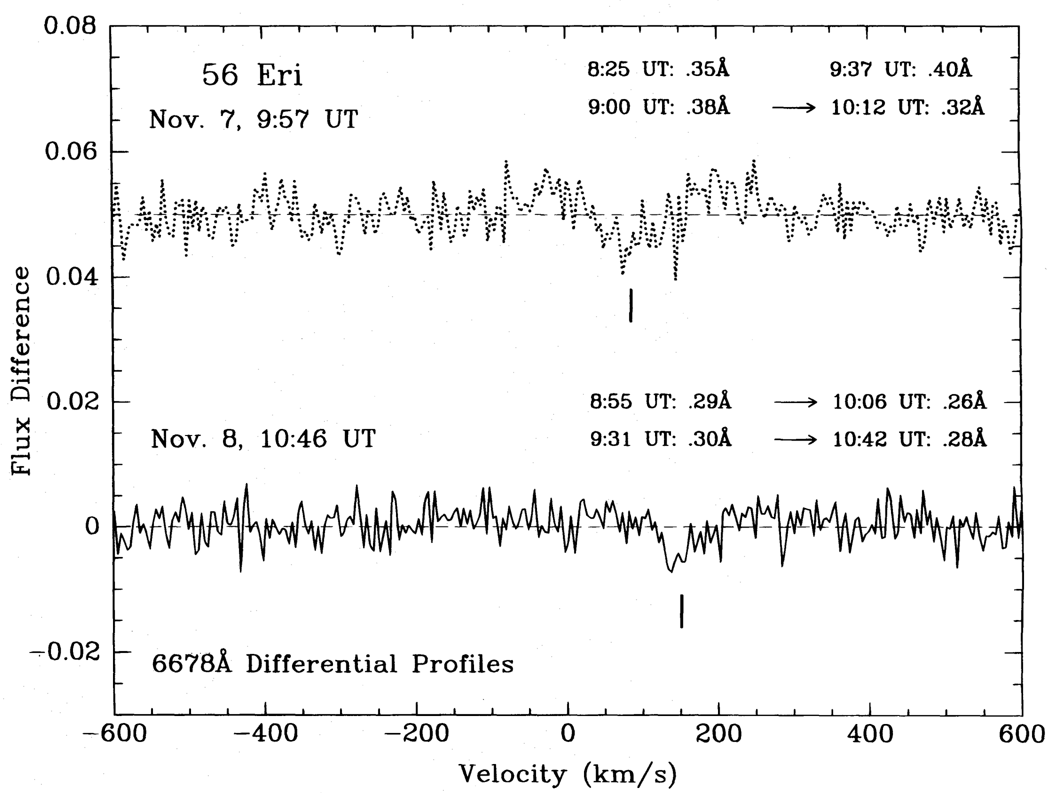

FIG. 9.—Difference profiles of a sequence of $\lambda6678$ line profiles for the mild B2e star 56 Eri on two nights showing subtle absorption and emission features (*heavy lines*). The times of the *IUE* observations and the equivalent widths of the C IV $\lambda1548$ line are indicated, showing a weakening at approximately the time an $\lambda6678$ line dimple is observed (*arrow*).

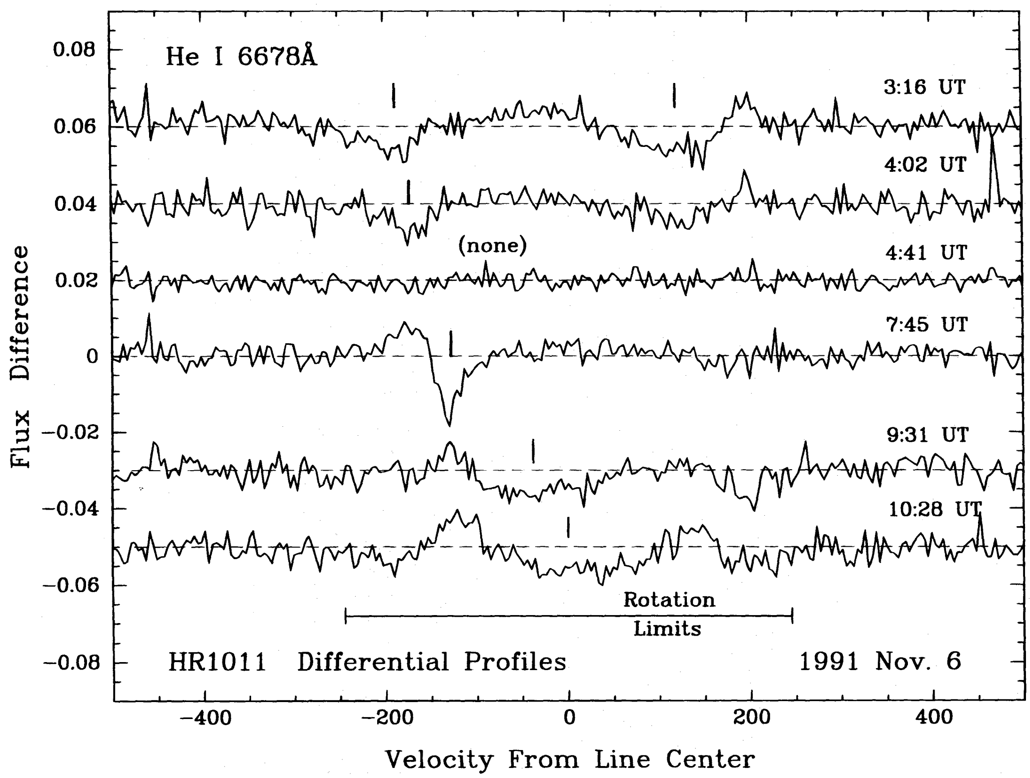

FIG. 10.—Difference profiles over several hours of the migrating subfeatures in the λ6678 line of HR 1011 (B5). Each of the frames shown is the average of two to three consecutive observations. Note the patterns of alternating absorption and emission features that recur every 250–300 km s^{-1}. The pattern is initially strong, disappears in the third frame, and grows again in the following frames. The migration pattern is consistent with the stellar rotation rate.

of several ions, is similar, even though the physics of the formation of each of these lines can be quite different. Recent unpublished observations of these features in γ Cas show that the subfeatures describe a sinusoidal velocity curve as they migrate across the profile consistent with rotational advection. A Doppler-imaging model of rising and falling slabs to account for alternately quasi-P Cygni/inverse-P Cygni–shaped dimples (SP93) can be generalized, in principle, to include lateral circulations of prominence with rising and falling streams. Such flows may rise and collapse onto "footpoints" on the star's surface, giving an alternating emission and absorption pattern in Doppler imaging. Single dimples are probably more prevalent on Be stars, occurring as single features and not usually recurring in the same place. Perhaps migrating subfeatures represent essentially the same phenomenon, but with more ordered outflows and returns of matter to the surface.

4. CONCLUSIONS

We have shown that dimples, formerly defined only in a narrow context of the λ6678 line of λ Eri, are visible in several optical He I lines. Dimples are also observable in the λ6678 line of four or five other mild Be stars and possibly γ Cas. The evidence is strong that dimples are not limited to just λ Eri but are endemic to a class of mild early-to-middle B/Be stars with rapid rotation. In agreement with SP93, we have found that the C IV lines tend to weaken with the emergence of optical line dimples. We do not know yet whether the line weakening is caused by a source function less prone to non-LTE overpopulation of the lower atomic level or whether to a bona fide incipient emission. The weakening of the C IV lines in λ Eri extends to the He II λ1640 line, which must necessarily be due to emission. We also notice that λ6678 microemissions and dimples appear with similar frequencies and that they evolve on comparable timescales (Smith et al. 1994b, 1997). Finally, Smith et al. (1997) have found that a 13% emission transient in the λ6678 line of λ Eri is caused by recombination from a gas parcel having a mass of 4×10^{-13} $M_\odot$. This mass is comparable to what we just estimated for a weak dimple. We conjecture that emissions and dimples are manifestations of the same kind of event, but perhaps operating in two different regions of parameter space. For example, the models of non-LTE processes in a slab situated above the atmosphere that were investigated by Smith et al. (1997) show that absorption, rather than emission, result in optical He I lines if either the slab's temperature is low ($< T_{\rm boundary}$) or if the optical depths in these lines are not quite so optically thick as they must be for the lines to appear in emission.

We may at last put together what has been learned about dimples to formulate a conjecture concerning the origin of dimples and their potential role in Be mass-loss episodes.

SP95 have pointed out that the characteristic propagation velocity of the formation of dimple slabs in λ Eri lines is $\approx$800 km s^{-1}. This is also the local escape velocity and therefore the velocity at which particles would evaporate from the atmosphere if exposed to a nearby high-energy source. According to the SP93 models, slabs are essentially stationary structures suspended $\sim$0.1–0.2R_* over the surface of a rapidly rotating star. We propose that a slab is the result of an explosive event that evaporates matter at the base of a closed magnetic loop in the photosphere. In our scenario, superheated plasma that is attempting to escape upward cannot cross traverse field lines in its path and is stopped abruptly. Here it cools to become a slab opaque in He I lines. Thus, slabs assume characteristics of quiescent prominences on the Sun. Our rationale for invoking a closed field line topology amounts to a process of elimination: it is the only reasonable way we can see for the material to be brought to a site at essentially the escape velocity from the star's surface and then constrained to stay there for hours as a stationary structure.

If one assumes that roughly three dimples are present over the λ Eri's surface at any moment and that each has a lifetime of 2 hr, then even low estimates of slab masses imply the injection of $\sim 10^{-12}\ M_{\odot}\ \mathrm{hr}^{-1}$ into loop regions above λ Eri. For the sake of comparison, a circumstellar disk of $10^{-11}\ M_{\odot}$ can be expelled from a Be star in 2 days (Peters 1986). Also note that $10^{-12}\ M_{\odot}\ \mathrm{hr}^{-1}$ released steadily into these slabs is comparable to the average mass-loss rate for classical Be stars, namely, $\sim 10^{-8}\ M_{\odot}\ \mathrm{yr}^{-1}$ (Waters, Cote, & Lamers 1987), and only a factor of 10 below the rate for "high"-mass losers like γ Cas ($\sim 10^{-7}\ M_{\odot}\ \mathrm{yr}^{-1}$; Waters et al. 1988; Stee et al. 1995). These mass release estimates permit a rather simple hypothesis to emerge: *what is different for Be stars in their emission and nonemission episodes may not be that a mysterious mass-loss mechanism must be turned on and off, but merely that the prevailing magnetic field topology at the star's surface be changed, from open lines to closed loops.* Still higher mass-loss rates, as found for γ Cas, may find their origin by a combination of larger filling factors and more energetic disturbances that ablate the photosphere down to greater depths.

In principle, any number of circumstances could lead to the opening of field loops, among them, the domination of magnetic loop pressure by momentum flux as mass continues to evaporate from a small area, or even the drifting together of two bipoles from differential stellar rotation. A third possibility is that surface regions on Be stars may alternate between opened and closed geometries, similar to those of "hybrid" cool stars. The usual criterion given for the opening of field lines from dipoles on stars is that the magnetic pressure at some height z above the surface exceeds the gas pressure (Rosner et al. 1995). The former drops off as z^{-6}, whereas the latter decreases more slowly. The condition that favors a prevailing open-line configuration is one in which surface dipoles are more compact, so that this condition is reached at a lower z. Thus, the third possibility could arise if the mean size of dipoles in a Be star changed from time to time. There are probably many more possibilities.

Lacking Zeeman polarization of dimple features in line profiles of Be stars, we cannot directly measure how strong these loops might be. Nonetheless, limits can be placed on their strength by requiring the magnetic pressure in loops to balance the energy of upward flowing particles. If a typical slab density is $\sim 3 \times 10^{-13}\ \mathrm{g\ cm^{-3}}$ (SP93) and particles flow outward at the escape velocity, then the field strength needed to balance them is 200 g. However, this estimate is likely to be a lower limit for at least two reasons. First, if the field were in a precarious balance, then one would expect that, during stronger events, plasma would break through the slabs, yet this is not observed. Second, the density given above is given as a lower limit by SP93. From these conditions, we can guess that these fields are substantially greater and are probably of the order of a kilogauss or higher. Fields of this strength and areal coverage are at last within detection limits of modern Zeeman analyzers. The detection of their signatures in line profiles of stars like λ Eri should be pursued vigorously in order to test these ideas.

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REFERENCES

Baade, D., & Balona, L. A. 1994, Pulsation, Rotation, and Mass Loss in Early-Type Stars, ed. L. Balona, H. Henrichs, & J. Le Contel (Dordrecht: Kluwer), 311
Barnard, A. J., Cooper, J., & Smith, E. W. 1974, J. Quant. Spectrosc. Radiat. Transfer, 14, 1025
Bolton, C. T., & Stefl, S. 1990, Angular Momentum and Mass Loss for Hot Stars, NATO/ASI Series C, vol. 316, ed. L. Willson & R. Stalio (Dordrecht: Kluwer), 191
Heasley, J. N., & Wolff, S. C. 1981, ApJ, 245, 977
Horaguchi, T., et al. 1994, PASJ, 46, 9
Hubeny, I. 1988, Comput. Phys. Commun., 52, 103
Marlborugh, J. M. 1995, ApJ, 440, 303
Mihalas, D., Barnard, A. J., Cooper, J., & Smith, E. W. 1975, ApJ, 197, 139
Peters, G. J. 1986, ApJ, 301, L61
Rosner, R., Musielak, Z. E., Cattaneo, F., Moore, R. L., & Suess, S. T. 1995, ApJ, 442, L25
Smith, M. A. 1989, ApJS, 71, 357
———. 1994, *IUE* Three-Agency Conf. Rep., ed. W. Wamsteker, unpublished
———. 1995, ApJ, 442, 812
Smith, M. A., Peters, G. P., & Grady, C. A. 1991, ApJ, 367, 302
Smith, M. A., Grady, C. A., Peters, G. P., & Feigelson, E. D. 1993, ApJ, 409, L49
Smith, M. A., Hubeny, I., & Lanz, T. 1994a, Pulsation, Rotation, and Mass Loss in Early-Type Stars, ed. L. Balona & H. Henrichs (Dortrecht: Kluwer), 273
Smith, M. A., Hubeny, I., Lanz, T., & Meylan, T. 1994b, ApJ, 432, 392
Smith, M. A., Cohen, D. H., Hubeny, I., Plett, K., Basri, G. S., Johns-Krull, C. M., MacFarlane, J., & Hirata, R. 1997, ApJ, submitted
Smith, M. A., & Polidan, R. S. 1993, ApJ, 408, 323 (SP93)
Stee, Ph., de Araujo, F. X., Vakili, F., Mourard, D., Bonneau, D., Morand, F., & Tallon-Bosc, I. 1995, A&A, 300, 219
Uesugi, A., & Fukuda, I. 1982, Revised Catalogue of Stellar Rotational Velocities (Kyoto: Kyoto Univ.)
Wasatonic, R. 1994, private communication
Waters, L. B., Cote, J., & Lamers H. J. 1987, A&A, 185, 206
Waters, L. B., Taylor, A. R., van den Heuvel, E. P., Habets, G. M., & Persi, P. 1988, A&A, 198, 200
Wolff, S. C., & Heasley, J. N. 1985, ApJ, 292, 589
Yang, S., Ninkov, Z., & Walker, G. A. H. 1988, PASP, 100, 233