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THE REMARKABLE ALTERNATING SPECTRA OF THE Of?p STAR HD 191612

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ABSTRACT

The spectrum of HD 191612 has been found to display large, recurrent variations between two highly reproducible, peculiar states; at least four transformations have occurred since 1950. In one state, the spectral type is O6–O7, with C III λ4650 emission comparable to N III λ4640 (the definition of the Of?p category) and P Cygni profiles at He II λ4686 and Hα. In the other state, the spectral type is O8, with the C III emission absent, very strong N III λ4097 absorption, broad He II λ4686 absorption with narrow central emission (a profile that may be unprecedented in this line among known O-type spectra), and a broad asymmetrical absorption at Hα. One observing sequence over several consecutive nights shows no spectral variations, practically ruling out a short-period, interacting binary as the origin of the phenomenon; moreover, no significant radial velocity variations have been found. Although the sporadic observational record prior to the discovery of the variations in early 2001 precludes definite conclusions, it is possible that a given state is maintained for a decade or longer, but one transformation occurred within 13 months, and the data obtained during 2002 suggest an event with a shorter timescale.

The Of?p category currently contains only five members: three in the Galaxy and two in the Small Magellanic Cloud. The other two Galactic members also display bizarre and unexplained phenomena; in the case of HD 108, they are strikingly similar to those described here. Because of their relatively high X-ray luminosities, all three Galactic objects have been suggested to have collapsed companions. If the spectral variations of HD 108 and HD 191612 are due to binary interactions, they are likely multiyear, eccentric systems like WR 140 and η Carinae. The axisymmetric shell ejections of HD 148937 could have a similar origin. Alternatively, these stars may be rapid rotators or in an unstable evolutionary transitional stage. Further intensive spectroscopic monitoring is required to reveal their nature.

Subject headings: stars: early-type — stars: emission-line, Be — stars: individual (HD 191612) — stars: mass loss — stars: variables: other

1. INTRODUCTION

The Of?p category was introduced by Walborn (1972a) to describe two well-known peculiar stars, HD 108 in the northern hemisphere and HD 148937 in the southern hemisphere. The question mark was intended to denote doubt that these stars are normal Of supergiants, as the latter class had recently been interpreted (Walborn 1971). The principal defining Of?p characteristic is the presence of C III $\lambda\lambda$4647, 4650, 4651 emission lines with strength *comparable* to that of N III $\lambda\lambda$4634, 4640, 4642. The N III emission lines are always much stronger than the C III in normal Of spectra, when the latter are present. Other Of?p spectral peculiarities include the presence of sharp absorption components and P Cygni profiles at some H and He lines, indicative of shell effects and enhanced mass loss. Nevertheless, the *selectivity* of the N III emission is maintained, i.e., N III λ4097 remains in absorption (Mihalas, Hummer, & Conti 1972; Walborn 2001); thus, these emission spectra are not nebular. A third member of the Of?p category, HD 191612 in Cygnus, was discovered by Walborn (1973), where widened photographic spectrograms of all three stars are reproduced. More recently, two examples in the Small Magellanic Cloud have been identified (Walborn et al. 2000; Massey & Duffy 2001).

At the time this empirical spectroscopic category was defined, there were some who questioned the distinction from normal Of spectra ("If it quacks like a duck…"). However, subsequent information has amply vindicated both the association of these objects with each other and their differentiation from Of supergiants. While the ultraviolet stellar-wind profiles of normal O stars display a strong luminosity (or wind density) dependence, the Of?p stars do not have supergiant wind profiles, which are instead peculiar in HD 108 or giantlike in HD 148937 (Bruhweiler et al. 1981 and references therein; Walborn, Nichols-Bohlin, & Panek 1985). A previously unpublished *IUE* observation of HD 191612 is shown in Figure 1; consistently, it shows a

[1] Operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.
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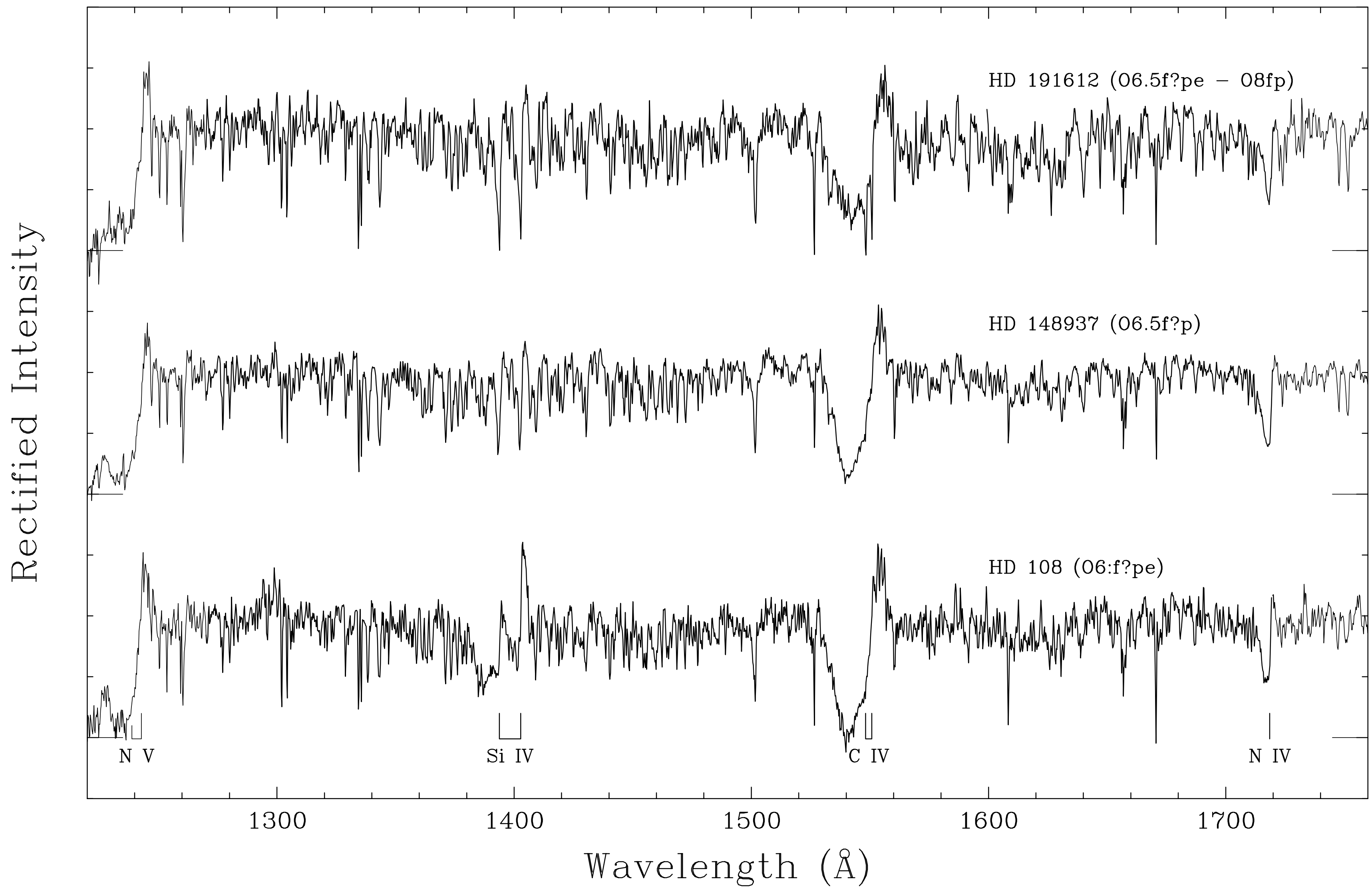

FIG. 1.—Rectified and rebinned (to 0.25 Å) *IUE* high-resolution observations of the Of?p stars HD 191612, HD 148937, and HD 108. The image numbers and original PIs are SWP 46531, Voels; SWP 2893, Conti; and SWP 13910, Conti, respectively. The date of the HD 191612 observation was 1992 December 19. The longer ordinate ticks mark the zero levels for each plot. The stellar-wind features identified below are N V $\lambda\lambda$1239, 1243; Si IV $\lambda\lambda$1394, 1403; C IV $\lambda\lambda$1548, 1551; and N IV λ1718. The weak Si IV profiles demonstrate that these stars are not normal Of supergiants; that of HD 108 is peculiar as well.

peculiar, nonsupergiant Si IV wind profile. Chlebowski (1989) found relatively high X-ray luminosities for all three of the Galactic examples and discussed them together as possible binaries with collapsed companions. Further compelling spectroscopic evidence linking HD 108 and HD 191612 will be presented here.

The optical spectrum of HD 148937 has been relatively little studied, perhaps because of its southern location and the distracting effect of its spectacular, ejected circumstellar nebulosities (Bruhweiler et al. 1981; Leitherer & Chavarría-K. 1987), although some suggestive stellar information was provided by Westerlund (1961), as quoted below. In contrast, HD 108 has a long history of spectroscopic investigation, which is nicely summarized and advanced by Nazé, Vreux, & Rauw (2001). They present an intensive monitoring campaign that revealed large, systematic spectroscopic variations with rather remarkable, albeit unexplained, characteristics. Our interest in HD 191612 was rekindled independently in early 2001, when inspection by N. R. W. of the observation discussed by Herrero et al. (1992) showed a completely different spectrum from the one observed by Walborn (1973). Subsequent studies of the historical record and new observations have revealed large, recurrent spectral variations essentially identical to those found in HD 108 by Nazé et al. (2001), as will be discussed. We are not yet able to offer a definitive explanation, either, but we firmly establish that HD 108 and HD 191612 (and probably HD 148937) exhibit the same mysterious phenomenon, and we draw comparisons with certain other categories of peculiar massive objects.

2. DATA

2.1. ≤1982

Following our detection of major spectral variability in HD 191612, the literature was surveyed for prior descriptions of its spectrum. Three significant reports in addition to that by Walborn (1973) were found, as listed in Table 1. All of these observations were photographic. The early O8 classification by Roman (1951) is highly significant in view of the source; it was repeated in several subsequent Yerkes publications, including Morgan, Code, & Whitford (1955), which are here assumed to refer to the same observation. The emission lines were not noted in this classification, but that is consistent with their relative weakness and the low prismatic dispersion in the green region of the spectrum.

The O7.5 III(f) classification by Conti (1973) and Conti & Leep (1974) is again very important, the more so in view of the slight horizontal shift with respect to the system of Walborn (1972a) noted by the latter. For instance, the fundamental O7 V((f)) morphological standard 15 Mon was measured as O8 III((f)) in the Conti system. The equivalent widths of He I λ4471 and He II λ4541 in HD 191612 listed by Conti (1973), Table 2, are essentially identical, so that this spectrum would most likely have been classified as O7 in the MK or Walborn systems. The note to Conti's (1973) table specifying that He II λ4686 had a P Cygni profile in his observation of HD 191612 will also be seen to be very important.

Walborn (1973) classified his observation of the spectrum of HD 191612 as O6.5f?pe. The presence of P Cygni profiles at Hβ and Hγ as well as a narrow absorption component at Hδ was noted, in addition to the C III λ4650 emission.

Fortunately, Peppel (1984) reproduces both his blue and red observations of HD 191612, adopting the spectral type of Walborn (1973), albeit with the addition of a luminosity class not assigned by the latter. The blue spectrum is clearly consistent with that type, and the C III λ4650 emission has similar strength to the N III λ4640. It is also significant that Hα and probably He II λ4686 have P Cygni profiles in Peppel's (1984) data.

It is interesting to note that differences in spectral classifications of this magnitude are often assumed to arise from variations in judgment or technique among observers. However, in studies of the quality cited above, such differences may well be real, as will be shown to be definitely true in the case of HD 191612.

TABLE 1
PHOTOGRAPHIC OBSERVATIONS OF HD 191612

Date	Resolution (Å)	Spectral Type	Reference
Circa 1950	2.5 at Hγ	O8	1
1971–1972	0.3	O7.5 III(f)	2
1972 Sep 24–25	1.2	O6.5f?pe	3
1982	1.0	O6.5 If?pe	4

REFERENCES.—(1) Roman 1951; (2) Conti 1973; (3) Walborn 1973; (4) Peppel 1984.

2.2. ≥1989

Our complementary responses to the detection of spectral variability in HD 191612 were to search available digital archives and to obtain new observations, with the results listed in Tables 2 and 3. All of these observations are digital and, with one exception, were obtained at the Isaac Newton or William Herschel Telescope on La Palma; the exception is the observation of 2002 September 11 obtained at the Steward Observatory Bok Telescope on Kitt Peak. Nearly all of the new data are illustrated in Figures 2–7. Figure 2 contains most of the available blue-violet data, with the higher resolutions reduced to that of the 1990 August 13 observation to facilitate intercomparison. Figure 3 again displays the blue(-green) data but restricted to the critical 4450–4750 Å range, which is essentially complete at all available epochs, and preserving the original resolutions, as indicated in the figure. Figure 4 contains the available coverage of the yellow spectral region. Figure 5 shows the dramatic, multiepoch red observations. Finally, Figures 6 and 7 record the blue and red results, respectively, from the concentrated 2001 August runs, which show no variations and for which the means are plotted in the earlier figures. The detailed contents of these figures will be discussed in § 3.

Differential radial velocities were measured in the blue-violet data, with respect to the 2001 August 5 observation as a cross-correlation template. The results are given in Table 2 and are accurate to one-tenth of a resolution element in the best cases (e.g., 7 km s^{-1} in the 2001 August sequence). Thus, no significant radial velocity variations have been detected in these data.

TABLE 2

Blue-Violet Digital Observations of HD 191612

Date	UT	Instrument[a]	Observer[b]	Exposure (s)	Resolution (Å)	ΔRV[c] (km s^{-1})	Comment
1989 Jul 17	03:59	INT/IDS	AHD	500	0.8	+5	Segments combined
	04:44			500			
	04:55			500			
	05:05			450			
	05:17			400			
	05:25			450			
	05:34			400			
	05:42			400			
1990 Aug 13	21:37	INT/IDS	IDH	200	1.5	−12	Segments combined
	21:42			200			
1993 Jun 1	04:37	INT/IDS	JMV	850	0.5	. . .	Segments combined
	04:55			700			
1994 Jun 25	21:14	WHT/ISIS	PAC	40	3.0	+7	
1997 Aug 23	00:27	WHT/UES	JT	480	0.1	+3	Violet echellogram
2001 Jul 11	02:45	INT/IDS	PE/AHD	780	0.5	+3	Segments combined
	04:01			780			
	04:20			780			
2001 Aug 5	21:58	WHT/ISIS	CJE/IDH	210	0.8	≡0	Spectrum constant during run
Aug 6	21:15			250	0.8	−1	
Aug 7	21:16			250	0.8	+2	
Aug 8	01:26			60	1.5	+3	
Aug 8	21:48			250	0.8	+5	
2002 Aug 20	17:19	INT/IDS	SAB/BTG	10	3.8	+21	Observations combined
Aug 21...................	17:16			10			
2002 Sep 11	07:26	Steward Bok	RMW/HEB	180	1.6	−1	Echellette
2002 Oct 1	20:02	WHT/ISIS	SE/SR/MP	170	2.0	+10	
2002 Oct 18	19:21	WHT/ISIS	PAC	110	0.8	−14	
2002 Nov 28	19:19	WHT/ISIS	CJE/PAC	90	3.0	−3	
2002 Dec 23..............	18:58	WHT/ISIS	TJH	700	0.7	+12	

[a] INT: Isaac Newton Telescope; IDS: Intermediate Dispersion Spectrograph; WHT: William Herschel Telescope; ISIS: Intermediate-dispersion Spectroscopic and Imaging System; UES: Utrecht Echelle Spectrograph.

[b] AHD: Herrero; IDH: Howarth; JMV: Vilchez; PAC: Crowther; JT: Trapero; PE: Erwin; CJE: Evans; SAB: Araujo; BTG: Gänsicke; RMW: Wagner; HEB: Bond; SE: Ellison; SR: Rix; MP: Pettini; TJH: Harries.

[c] Differential heliocentric radial velocity relative to 2001 August 5 as cross-correlation template.

3. RECURRENT SPECTRAL VARIATIONS

3.1. *Two Spectral States of* HD 191612

The only one of our digital observations that has been discussed previously in the literature to our knowledge is the first blue-violet one, from 1989 July 17, which was analyzed by Herrero et al. (1992). The later comparison of this observation with the spectrogram of Walborn (1973) revealed the spectral variability of HD 191612. Herrero et al. (1992) discussed it essentially as a normal spectrum but noted an excessively deep core in He I λ4471, as well as the peculiar profile of He II λ4686, which could not be fitted by the models. Although it was not used to determine their effective temperature, Herrero et al. (1992) adopted the O6.5 spectral type from Walborn (1973), whereas the spectral type of their observation was actually O8. Their derived temperature is more appropriate for the earlier type, however; a lower value would have fitted λ4471 better, but then the fits to other lines would have been worse. At O6.5, He I λ4471 is weaker than He II λ4541, but at O8 the He I line is much stronger than the He II; the spectral type O7 is defined by equal strengths of these two lines in the morphological classification (Walborn & Fitzpatrick 1990), and the reversal of the ratio on either side of that type provides a very sensitive classification criterion. Thus, the results of Herrero et al. (1992) already indicated that HD 191612 is a peculiar star.

Inspection of Figures 2 and 3 shows two well-defined, recurrent spectral states in HD 191612, with some possible evidence for an intermediate (transitional?) state that requires confirmation from additional data. One, hereafter the O8, state corresponds to the 1989 and 2001–2002 observations, while the other, hereafter O6-7, occurs in the 1990–1997 data. The 1994 (O7) observation may be intermediate, but it has low resolution and only partial wavelength coverage. The characterization of the 1997 violet fragment as O6-7 is based on only the relative weakness of He I + II λ4026, but it is supported by the contemporaneous red observation discussed below. Evidence for a trend in the 2002 data will also be discussed below.

In addition to the spectral type from the He I and He II absorption lines, the O8 state displays the following remarkable peculiar features. Amazingly, the C III λ4650 emission that defines the Of?p category is absent, or only very weakly present in the best data! Moreover, the profile of He II λ4686, consisting of a narrow emission line within a broader absorption feature (of which only the wings are visible) is unprecedented for this line in our experience of O-type spectra. Finally, the great strength of the N III λ4097 absorption

TABLE 3

Red Digital Observations of HD 191612

Date	UT	Instrument[a]	Observer[b]	Exposure (s)	Resolution (Å)
1989 Jun 14	01:32	INT/IDS	RKP/IDH	360	0.5
	23:39			360	
Jun 15	23:38			400	
1989 Jul 19	00:13	INT/IDS	AHD	100	1.5
	01:13			80	
	01:16			80	
1997 Aug 23	00:37	WHT/UES	JT	350	0.1
	00:45			20	
2001 Aug 5	21:58	WHT/ISIS	CJE/IDH	180	0.8
Aug 6	21:15			200	
Aug 7	21:16			200	
Aug 8	01:26			60	
Aug 8	21:48			200	
2001 Aug 11	03:53	INT/IDS	AHD	150	0.6
2002 Jul 28	01:07	INT/IDS	AHD	240	0.6
2002 Aug 20	17:19	INT/IDS	SAB/BTG	10	3.8
Aug 21	17:16			10	
2002 Sep 11	07:26	Steward Bok	RMW/HEB	180	2.6
2002 Oct 1	20:02	WHT/ISIS	SE/SR/MP	40	1.7
2002 Oct 18	19:21	WHT/ISIS	PAC	100	0.8
2002 Nov 28	19:17	WHT/ISIS	CJE/PAC	120	3.1

[a] INT: Isaac Newton Telescope; IDS: Intermediate Dispersion Spectrograph; WHT: William Herschel Telescope; UES: Utrecht Echelle Spectrograph; ISIS: Intermediate-dispersion Spectroscopic and Imaging System.

[b] RKP: Prinja; AHD: Herrero; JT: Trapero; CJE: Evans; IDH: Howarth; SAB: Araujo; BTG: Gänsicke; RMW: Wagner; HEB: Bond; SE: Ellison; SR: Rix; MP: Pettini; PAC: Crowther.

combined with the weak Si IV λ4089 shows at once that the star is not a supergiant (in agreement with the ultraviolet Si IV wind profile shown above) and suggests that there may be an enhanced nitrogen abundance in the material producing this spectrum; these two lines have comparable, positively luminosity-dependent strengths in normal spectra at this type (Walborn & Fitzpatrick 1990).

In striking contrast, the O6-7 state is further characterized by the strong Of?p C III λ4650 emission lines, in correlation with an emission-dominated P Cygni profile at He II λ4686. There is also an incipient, absorption-dominated P Cygni profile at He I λ4471 in the high-resolution 1993 observation; it is possible that some of the apparent spectral type variation may be caused by emission effects in this line. In this observation it can also be seen that the Si III $\lambda\lambda$4552, 4568, 4575 triplet has come into emission, as opposed to the absorption present in the O8 state. In the low-resolution 1994 observation, the apparent spectral type is O7, rather than O6.5 as in 1990 and 1993, and the C III emission and λ4686 P Cygni profile appear relatively weaker, possibly indicating an intermediate state, but as already mentioned, that interpretation requires further evidence.

Figure 4 shows the available data covering the yellow region of the spectrum. The content of this region is not unusual for the spectral types and is similar to that of HD 148937 (Walborn 1980). The 1994 observation corresponds to the O6-7 state, and the 2002 ones correspond to the O8 state. The ratio of He II λ5411 to He I λ5876 changes in the expected sense between the two states. Other features remain invariant in these data, most interestingly the C III λ5696 selective emission line (Walborn 2001); recall that the C III λ4650 emission disappears in the O8 state. The contrasting behavior of these C III lines may indicate that there are no abundance differences between the two spectral states; in any event, it provides a strong constraint on the nature of the variations.

The red region of the spectrum shown in Figure 5 undergoes even more extreme transformations; indeed, some of us experienced difficulty initially believing that these observations correspond to the same star! (However, the positional information transmitted directly to the data file headers by the telescope control systems is consistent with this isolated bright O star in all cases.) In particular, Hα changes from a peculiar, asymmetrical absorption feature in the O8 state, to a strong, emission-dominated P Cygni profile (analogous to He II λ4686) in the O6-7. At the same time, He I λ6678 varies from a weak to a strong P Cygni profile.

The 2002 data show evidence of a trend. Considering first the 2002 July 28 red observation in Figure 5, one sees P Cygni profiles of intermediate strength in Hα and He I λ6678. Despite the low resolution, the 2002 August 20–21 Hα profile is intermediate between the earlier and later ones, with a steeper red wing than later, indicating a residual P Cygni effect. The 2002 blue-violet data in Figures 2 and 3 corroborate the presence of a trend. The central-depth ratios of He II λ4541/He I λ4471 in the August–October observations are 0.64, 0.59, 0.54, and 0.52 in chronological order, while there appear to be related changes in N III λ4097 and He II λ4686 (although the different resolutions must be noted). That is, the spectral type and peculiar features are changing consistently in a direction from O6-7 to O8 states. In contrast, the constant 2001 August sequences displayed in Figures 6 and 7 demonstrate that the spectral transformations of HD 191612 do not occur on a daily timescale.

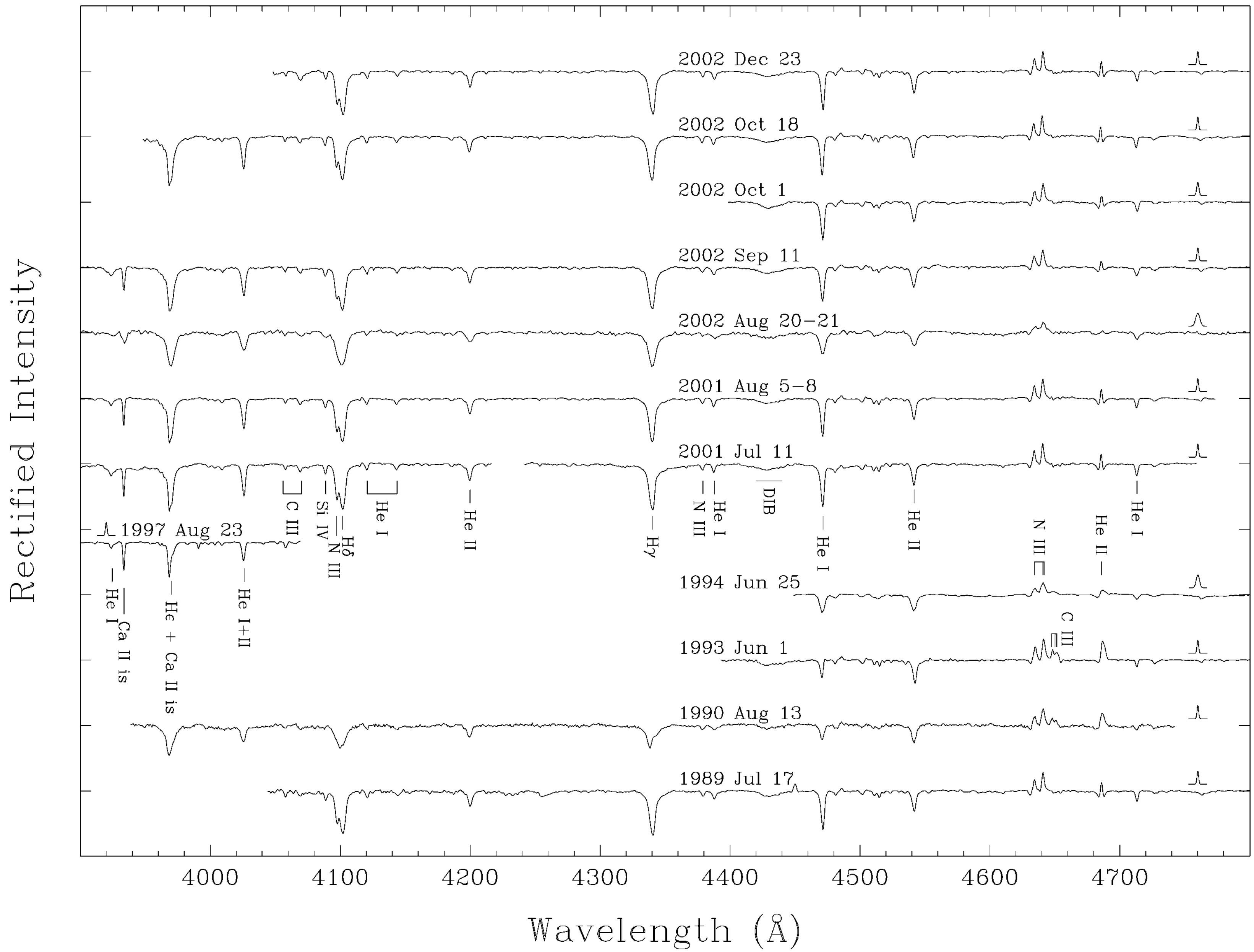

FIG. 2.—Full available blue-violet ranges in the digital observations of HD 191612 (except for 2002 November 28). The spectrograms are rectified, and the ordinate ticks are spaced by 0.5 continuum units; the higher resolution data have been smoothed to facilitate intercomparison, as indicated by the insets above each plot. The spectral lines identified, from left to right by ion, are He I $\lambda\lambda$3926, 4026, 4121, 4144, 4387, 4471, and 4713; interstellar Ca II $\lambda\lambda$3933, 3968; Hϵ λ3970, Hδ λ4102, Hγ λ4340; C III $\lambda\lambda$4056 (+N IV λ4058?), 4070, and 4647, 4650, 4651 (emission); Si IV λ4089; N III $\lambda\lambda$4097, 4379, and 4634, 4640, 4642 (emission); He II $\lambda\lambda$4026, 4200, 4541, and 4686 (emission); and the unidentified diffuse interstellar band λ4430. The 1989 and 2001–2002 observations correspond to the O8 state, while the 1990–1997 data exhibit the O6-7 state.

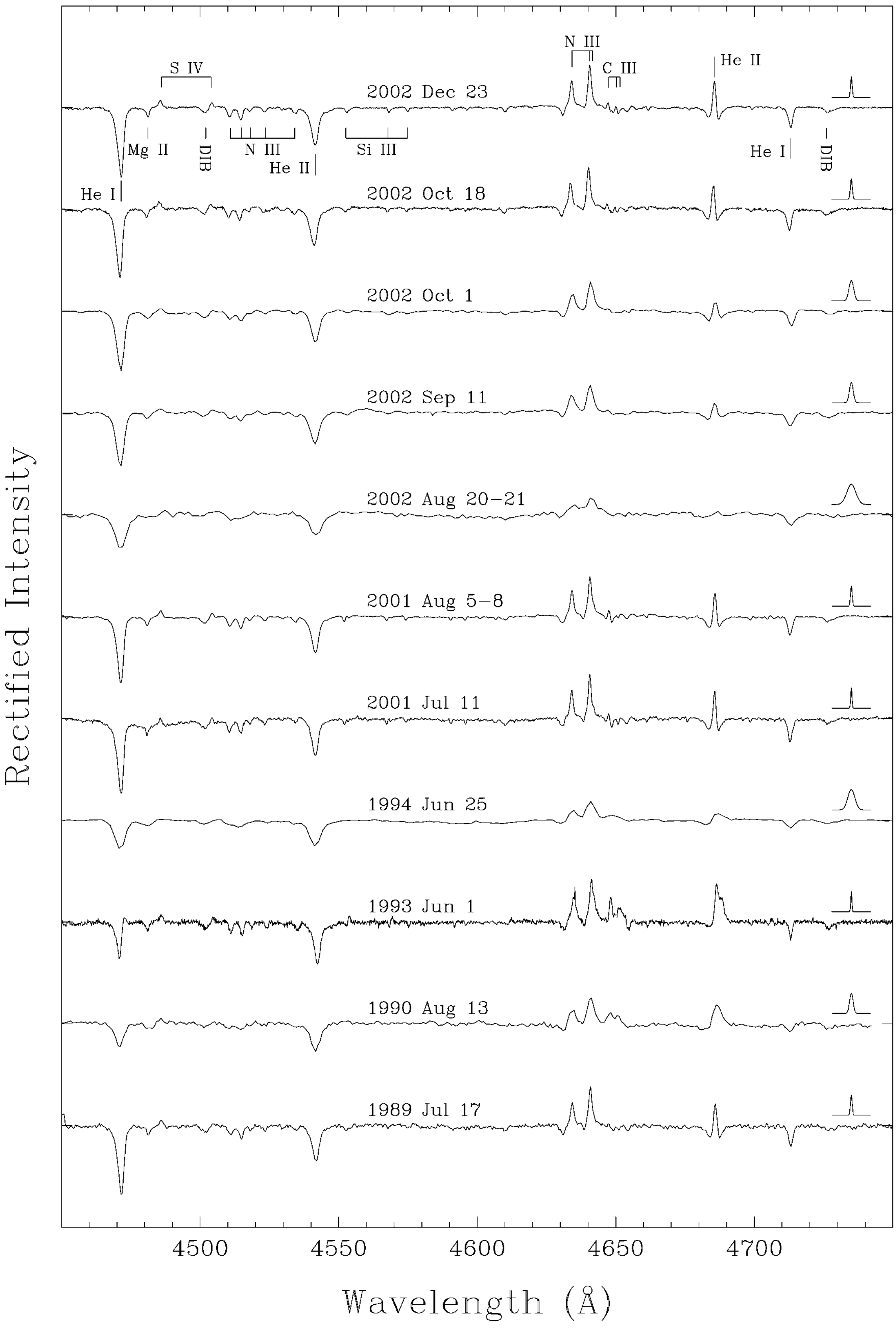

Fig. 3.—Green region in the digital spectrograms of HD 191612 at a larger scale. The plots are separated by 0.5 continuum units, and the original resolutions are preserved as indicated by the insets. The spectral lines identified are He I $\lambda\lambda$4471, 4713; Mg II λ4481; S IV $\lambda\lambda$4486, 4504 (emission); unidentified diffuse interstellar bands $\lambda\lambda$4502, 4726; N III $\lambda\lambda$4511, 4515, 4518, 4524, 4535, and 4634, 4640, 4642 (emission); He II $\lambda\lambda$4541, and 4686 (emission); Si III $\lambda\lambda$4552, 4568, 4575; and C III $\lambda\lambda$4647, 4650, 4651 (emission). Again, the 1989 and 2001–2002 observations correspond to the O8 state, while the 1990–1997 data exhibit the O6-7 state.

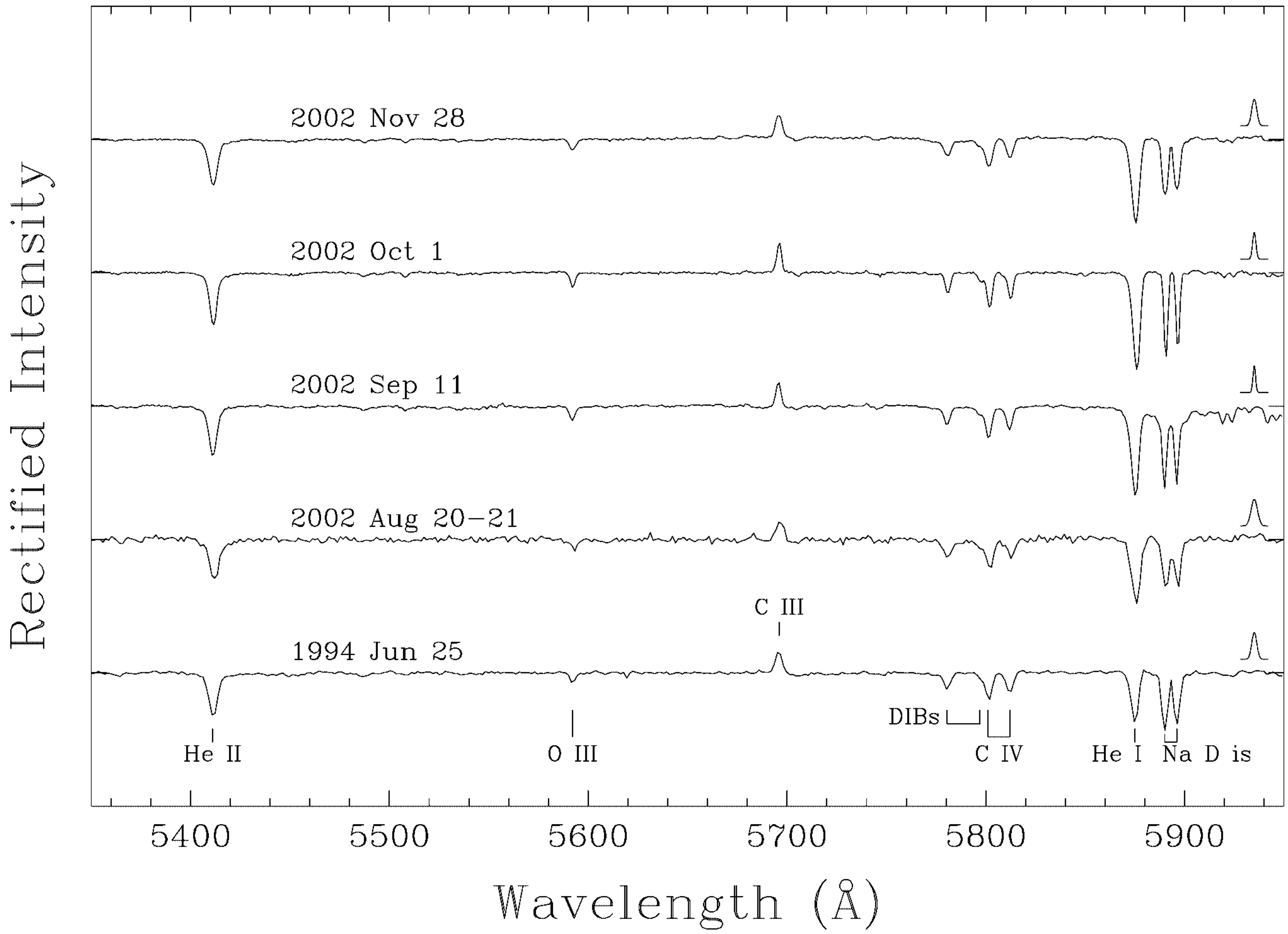

FIG. 4.—Available coverage of the yellow spectral region in HD 191612. The ordinate ticks are separated by 0.5 continuum units, and the insets show the respective resolutions. The spectral lines identified are He II $\lambda5411$, O III $\lambda5592$, C III $\lambda5696$ (emission), unidentified diffuse interstellar bands at $\lambda\lambda5780$–5797, C IV $\lambda\lambda5801$–5812, He I $\lambda5876$, and interstellar Na I D $\lambda\lambda5890$–5896. The 1994 observation corresponds to the O6-7 state, and the 2002 ones correspond to the O8. Note the invariance of C III $\lambda5696$, in contrast to C III $\lambda4650$, which disappears in the O8 state (Fig. 3).

To summarize the full observational record presented above, four transitions between the two spectral states of HD 191612 have been documented. In or about 1950, it was in the O8 state. In 1971–1972 and 1982, it was observed in the O6-7 state. The first digital observation in 1989 found it in the O8 state again. But all available observations between 1990 and 1997 correspond to the O6-7 state. Finally, the 2001–2002 observations following the discovery of the variability again display the O8 state. Of course, the sporadic nature of the record allows the possibility of additional, unobserved transitions. Nevertheless, there is a suggestion that a given state, especially the O6-7, may last for the order of a decade, or perhaps a few years for the O8. The transition from O8 to O6-7 between 1989 and 1990 occurred within 13 months. However, the 2002 observations introduce further uncertainty into the picture: do they represent a minor event, or are they revealing the end of a major one? In the latter case, the full transformation can occur within a year, and the consistent 1990–1997 O6-7 state is an observational fluke. It is unfortunate that coverage earlier in 2002 could not be obtained. Clearly, systematic seasonal monitoring from observatories with a synoptic capability is required to establish the actual timescales of the states and the transitions between them, and to search for any periodicity, in HD 191612.

3.2. *Stellar Parameters and Mass-Loss Rates*

It is clear that HD 191612 is not a normal star and that its spectrum contains peculiar features in both states; thus, definitive quantitative parameters must await an understanding of its actual structure and the variations. Nevertheless, preliminary estimates of the stellar parameters and mass-loss rates corresponding to the two spectral states have been made by A. H. D. using FASTWIND (Herrero, Puls, & Najarro 2002). The stellar parameters are first derived from the blue-violet spectra; they are then used to derive mass-loss rates from Hα. The O8 state is represented by the blue and red 2001 August mean data. The O6-7 Hα profile is that of 1997 August 23; since there are no contemporaneous blue data, it is assumed that the 1990 August 13 observation is representative of that state. The results are listed in Table 4 and discussed below.

Because of the spectral peculiarities, several nonstandard procedures and results were incurred, which will be described here. An M_V of -5.8 was adopted from Humphreys (1978) and assumed to apply to the O6-7 state. (Note that this value is based on the presumed membership of HD 191612 in Cygnus OB3 and that it corresponds to a giant luminosity class, in agreement with the indications from the ultraviolet stellar-wind profiles; Walborn 1973).

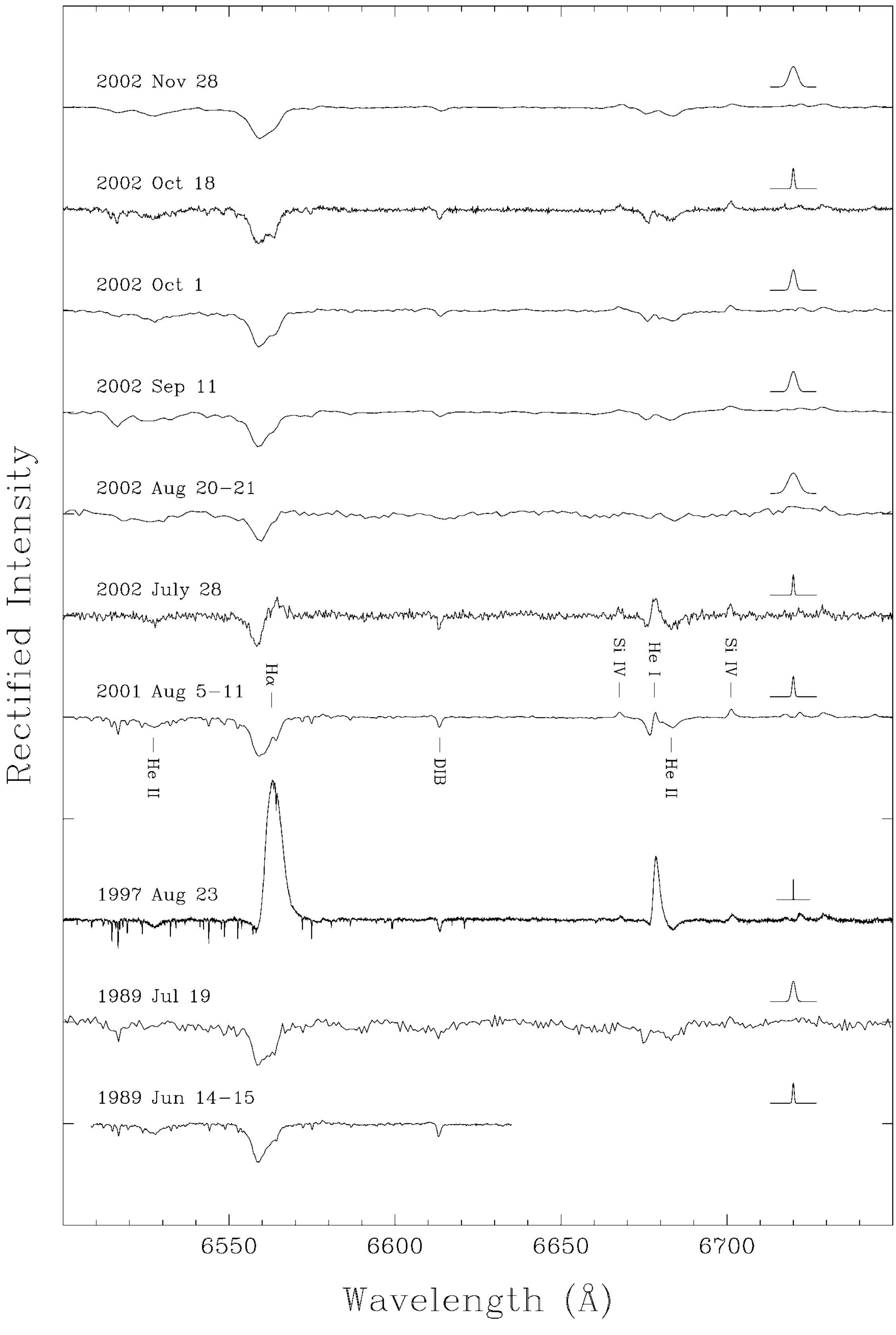

FIG. 5.—Available digital observations of the Hα region in HD 191612. The ordinate ticks are separated by 0.5 continuum units, and the insets show the respective resolutions. The spectral lines identified are He II λλ6527, 6683; Hα λ6563; unidentified diffuse interstellar band λ6614; Si IV λλ6667, 6701 (emission); and He I λ6678 (emission). The 1989, 2001, and 2002 August–November observations correspond to the O8 state, while the 1997 observation is believed to represent the O6-7 state and the 2002 July observation appears intermediate; unfortunately, there are no blue data contemporaneous with the latter two red observations.

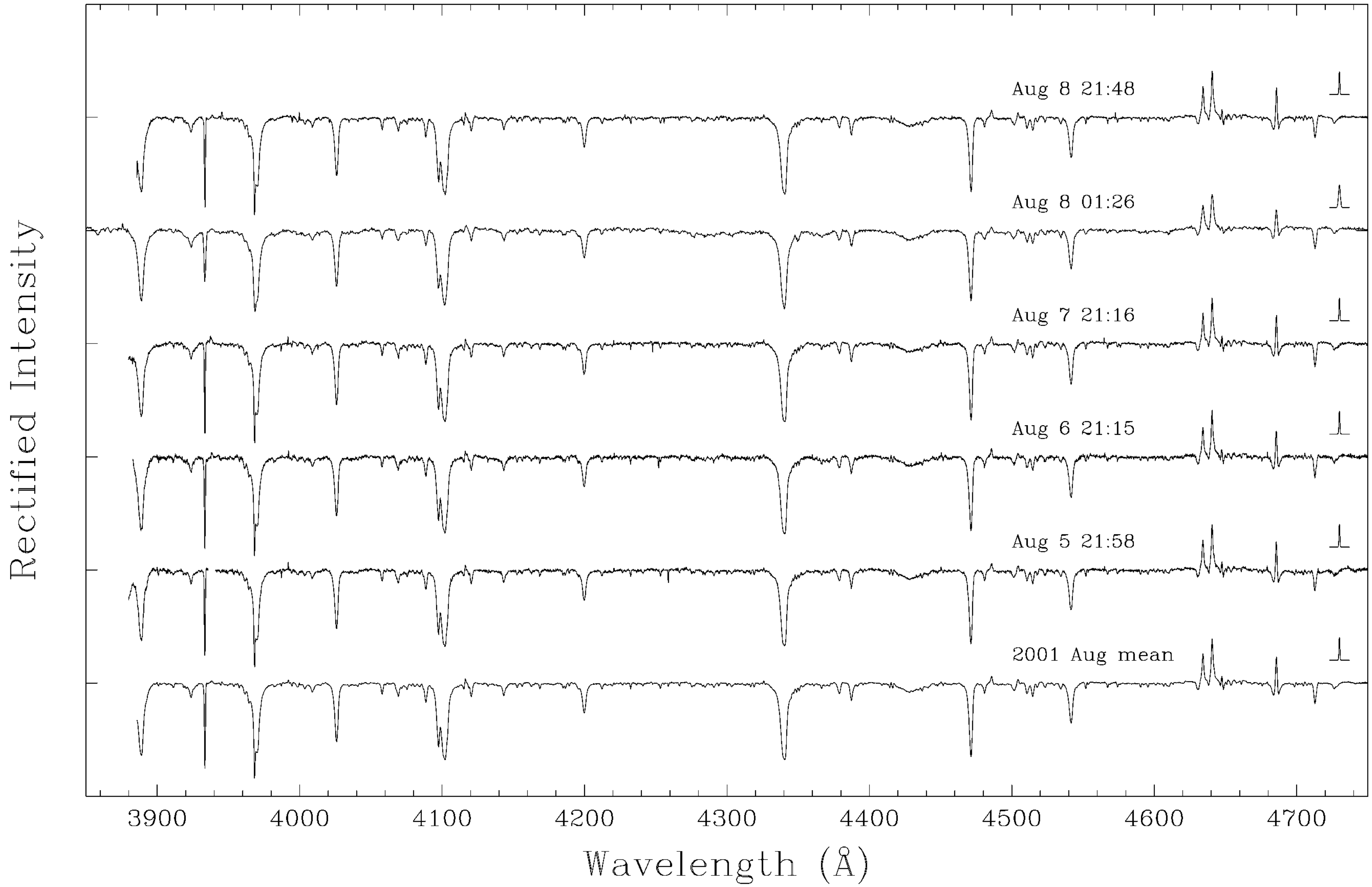

FIG. 6.—Digital observations of the blue-violet spectrum of HD 191612 during four consecutive nights in 2001 August, demonstrating constancy during that period. The plots are separated by 0.5 continuum units, and the insets show the resolution of each. The mean excludes the lower resolution observation of August 8. Spectral features are identified in the legends of Figs. 2 and 3.

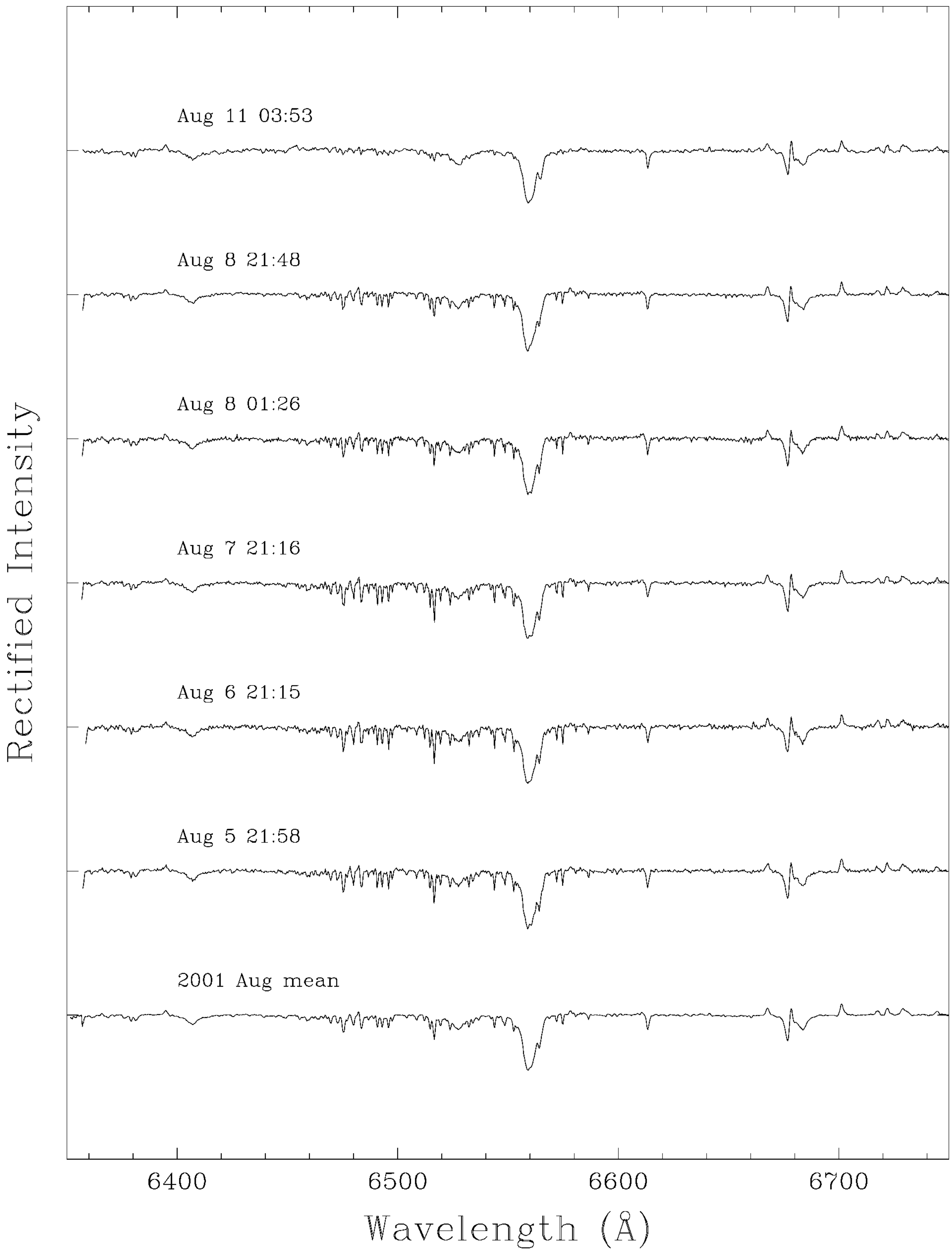

FIG. 7.—Digital observations of the red spectrum of HD 191612 during five nights in 2001 August, demonstrating constancy during that period. The plots are separated by 0.5 continuum units. Spectral features are identified in the legend of Fig. 5.

TABLE 4
ADOPTED AND DERIVED PARAMETERS FOR THE TWO STATES OF HD 191612

Parameter	O6-7 State	O8 State
$T_{\rm eff}$ (K)	37,000	35,000
$\log g$ (cgs)	3.65	3.55
He/H (number)	0.075	0.075
$v \sin i$ (km s^{-1})	80/200(?)	80
Microturbulence (km s^{-1})	5	5
M_V	−5.8	−6.0
$R/R_\odot$	16.7	18.7
$\log L/L_\odot$	5.67	5.67
v_∞ (km s^{-1})	2600	2100
$\dot{M}$ ($M_\odot$ yr^{-1})	6.1×10^{-6}	2.5×10^{-6}

The mass and luminosity of the star were assumed constant; since different gravities and temperatures are derived for the two spectral states, the radii must also be different. Slight adjustments were made to the derived parameters to obtain the same radius for each state from these two constraints. It follows that M_V and thus V must also change between states; in principle, an observational test of the analysis is implied.

Some line profiles in the spectra are not well fitted by these (or any) models. For instance, in the O6-7 state (only) the He I lines require an apparent $v \sin i$ of 200 km s^{-1}, while the He II and metal lines require 80 km s^{-1}. Interestingly, this discrepancy is identical to that between the optical and ultraviolet rotational velocities of HD 148937, discussed later. In the O8 state, the observed He I λ4471 is much too strong to be fitted with any reasonable parameter combinations. In any event, the derived He/H indicates unprocessed material, although N/C could still be anomalous if material from an early stage of hydrogen burning were present.

The wind terminal velocities are adopted, with reference to the *IUE* observation (from 1992 December 19) for the O6-7 state and with consideration of the relative escape velocity for the O8. The mass-loss rate of the O8 state has been derived by fitting the Hα profile, but in the O6-7 state only the equivalent width has been matched. Fitting the latter peculiar profile would require a far more detailed, specific model, which again implies an understanding of the actual wind structure. Thus, we find that the mass-loss rate in the O6-7 state is 2.4 times higher than in the O8. In view of the analysis anomalies, however, these results should be regarded as estimates, and no formal errors can be given in Table 4. Of course, the mass-loss rate results apply on the assumption of spherical symmetry. If the wind is not spherically symmetric, they are likely to be upper limits, although it is also possible that the largest mass fluxes may not be observed in that case because of orientation effects.

3.3. *Comparison with* HD 108 *and* HD 148937

HD 108 has a long observational history that is well summarized by Nazé et al. (2001), who also present the results of a 15 yr spectroscopic monitoring campaign of this star. The detailed correspondences between their results and the behavior of HD 191612 described above are striking. During their observations, the intensity of both the C III λ4650 emission relative to N III λ4640 and the P Cygni emissions at H and He I lines declined continuously; that is, these emission features are correlated just as in HD 191612. The Si III triplet behaved similarly while the S IV lines (not yet identified in their paper; Werner & Rauch 2001) remained constant, again as in HD 191612. Concentrated observing runs of several consecutive days showed no variations either in line profiles or in radial velocities. There do appear to be long-term radial velocity variations in their data with a possible 12.6 yr period, but the latter had low significance essentially because it is comparable to the duration of the observations, so it was discounted. Historical observations reviewed by Nazé et al. (2001) indicate that the line-profile variations of HD 108 are recurrent on a timescale of decades.

In contrast, there is relatively little information available about the optical spectrum of HD 148937, particularly with regard to variability. Westerlund (1961) provided some tantalizing hints, based on inspection of a number of photographic spectrograms at Mt. Stromlo: "the spectral lines are apparently variable. The hydrogen lines are in absorption. They are fairly broad and shallow with, in some cases, a sharp central core [cf. Walborn 1973]. Most other absorption lines have a similar appearance. This may indicate a rotating star with an outer shell. Practically all spectra have He II λ4686 in emission, most of them also N III λ4641 and a few also have C III (?) λ4651." That is, the C III/N III emission ratio is evidently variable, as is well documented in HD 108 and HD 191612. Conti, Garmany, & Hutchings (1977) performed an intensive radial velocity study of HD 148937 and concluded that it is constant. Line-intensity variations of the magnitude discussed here would presumably have been obvious in their high-resolution photographic material, but their only comment in that regard is that the λ4686 "profile appears variably asymmetrical." However, all of their data were obtained in four consecutive years, so variations on the timescales indicated for the other two stars might not have been covered. Nota et al. (1996) display a very high-quality single observation from 1991 that is consistent with other descriptions, except for weak emission reversals in blue Balmer lines that would be unusual unless they are nebular.

As discussed in § 1, the ultraviolet spectra of the three Galactic Of?p stars are similar in that they do not have supergiant stellar-wind profiles, as normal Of stars do. From both the optical and ultraviolet spectroscopic behavior, it can be concluded that HD 108 and HD 191612 definitely, and HD 148937 probably, exhibit the same mysterious physical phenomenon. HD 148937 differs from the other two stars by way of its spectacular, ejected circumstellar nebulosities, further discussed below. If HD 148937 is indeed properly grouped with the other two stars, these nebulosities will provide important clues to the nature of the Of?p phenomenon.

4. POSSIBLE ORIGINS OF THE PHENOMENON

4.1. *Interacting Binaries*

The spectral variations of HD 191612 immediately suggest the possibility of an interacting close binary. Several massive systems are known that display large, phase-dependent spectral variations, in some cases including apparent changes in the relative CNO line intensities; examples are Plaskett's star (HD 47129, O8p, 14.4 days: Hutchings & Cowley 1976; Bagnuolo & Barry 1996; N. Morrell & P. Massey, private communication), 29 UW CMa

(HD 57060, O7 Ia:fp var, 4.4 days: Hutchings 1977; Bagnuolo et al. 1994), V453 Sco (HD 163181, BN0.5 Iae, 12.0 days: Walborn 1972b; Hutchings 1975; Kane, McKeith, & Dufton 1981; Josephs et al. 2001), RY Sct (HD 169515, O9.7 Ibpe var, 11.1 days: Cowley & Hutchings 1976; Walborn 1982a; Smith et al. 2002), and V729 Cyg (BD $+40°4220$ = Cyg OB2-5, O7 Ianfp, 6.6 days: Bohannan & Conti 1976; Rauw, Vreux, & Bohannan 1999). However, observations of HD 191612 during four consecutive nights, plus another observation three nights later, showed no spectral variations (Figs. 6 and 7), and we have detected no significant radial velocity variations in any of our data, thus practically ruling out a short-period binary interpretation.

It is perhaps not ruled out by the data that HD 191612 might be a long-period binary in an eccentric orbit, with spectral variations or transitions induced by the periastron passage. In that case, the system could be related to the episodically dust-producing, WC binary WR 140 (HD 193793, 7.9 yr: Williams et al. 1990; Monnier, Tuthill, & Danchi 2002) and possibly η Car (HD 93308, 5.5 yr: Damineli et al. 2000; Corcoran et al. 2001), which displays periodic circumstellar ionization and X-ray events. That possibility is barely allowed by the available information, however; establishment of a period and observations at periastron would be required to confirm it. In this connection, the suggestion of collapsed companions for the Of?p stars by Chlebowski (1989) should be recalled; in that case, the secondary masses and hence radial velocity amplitudes would be small.

4.2. *Rapid Rotators*

Composite Balmer profiles with sharp and diffuse components were noted in HD 148937 by Westerlund (1961) and in HD 191612 by Walborn (1973); the former suggested an interpretation as a rotating star with a shell. Direct determinations of $v \sin i$ are available for all three Galactic Of?p stars. Conti & Ebbets (1977) derived 100:, 200, and 110 km s^{-1} from optical spectrograms of HD 108, 148937, and 191612, respectively. By cross-correlation analysis of *IUE* high-resolution data, Howarth et al. (1997) derived quite similar, lower values of 78 and 76 km s^{-1} for the first two stars, respectively, while 77 km s^{-1} has been determined here for HD 191612 by the same technique. Also with that technique, Penny (1996) found 74 and 92 km s^{-1} for HD 108 and 148937, respectively. Except for the discordant high optical value for HD 148937, these results are in reasonable agreement and do not indicate particularly high rotational velocities; rather, they are typical of the majority of O-type stars and are usually interpreted as atmospheric motions rather than rotation because of the lack of much smaller values. On the basis of Conti & Ebbets' (1977) result, Leitherer & Chavarría-K. (1987) proposed a model of the HD 148937 nebulosities as polar ejecta from a rapid rotator. In view of the (possibly variable) appearance of the Balmer profiles, the Conti & Ebbets (1977) result for HD 148937 should not be discounted; perhaps the UV-optical discrepancy might be real and indicative of a complex structure with slowly rotating extended material above a rapidly rotating underlying star. Alternatively, note that this discrepancy is identical to that found in the present analysis above, between the He I and other lines in the *same* spectrum of HD 191612 in the O6-7 state; perhaps the higher value is not rotational but due to some other line-broadening effect. In fact, inspection of He I λ4471 in the 1993 observation at full resolution shows that it is broader than the He II and metal lines, but with an asymmetrical shortward wing unlike the latter, suggesting that the He I line is formed through a greater range of the expansion velocity gradient.

At least two kinds of rapidly rotating O-type stars are known: the Oe analogs of the Be stars (Walborn 1971, 1980; Conti & Leep 1974; Conti & Ebbets 1977), and the Onfp (Walborn 1972a, 1973) or Oef (Conti & Leep 1974) class. In the former group, evidence of rotating disks is seen in the Balmer profiles, but in the latter it is seen in He II λ4686. If the Of?p stars are also rapid rotators, an obvious question is the reason(s) for the different spectral morphologies among the three groups. An entirely speculative suggestion is that it might prove worthwhile to search for magnetic phenomena in the Of?p stars. If they were oblique rotators and their winds had a magnetic latitudinal dependence, the spectral variations might be explained. Alternatively, a precessing rotational axis could produce such variations. Smith (2002) has demonstrated a latitudinal dependence in the wind of η Car, from the spatial variations of its spectrum as reflected by the circumstellar nebula.

4.3. *Luminous Blue Variables*

When the Ofpe/WN9 class in the Large Magellanic Cloud (LMC) was first described, one suggested point of comparison was the Of?p class in the Galaxy because of certain spectroscopic similarities such as He I and Si III emission lines, in addition to the Of features (Walborn 1977, 1982b). Ironically, in the meantime the Ofpe/WN9 stars have become rather better understood (Bohannan & Walborn 1989; Schmutz et al. 1991; Crowther, Hillier, & Smith 1995; Nota et al. 1996; Crowther & Smith 1997; Pasquali et al. 1997a, 1997b), while as described here, the Of?p stars have become even more enigmatic, so that the reverse comparison may now be appropriate! In particular, one of the prototype Ofpe/WN9 stars, HDE 269858 = Radcliffe 127, subsequently developed a classical luminous blue variable (LBV) outburst (Wolf et al. 1988 and references therein), thus establishing the prior hotter spectrum as the quiescent LBV state and suggesting a similar interpretation of other members of the class. No major outburst has yet been observed in an Of?p star, but given their lower level variability and similarities to the Ofpe/WN9 objects, the possibility that the Of?p class also represents an unstable, transitional evolutionary state must be considered. An additional object that is relevant to these comparisons is the Ofp exciting star of the LMC compact nebula N82, whose remarkable spectrum containing C III emission lines stronger than N III is so far unique in detail (Heydari-Malayeri & Melnick 1992).

A fundamental characteristic of most if not all LBVs and Ofpe/WN9 stars is their association with axisymmetric, nitrogen-rich ejected nebulae (Nota et al. 1995; Smith et al. 1998; Pasquali, Nota, & Clampin 1999; Lamers et al. 2001). The spectacular ejected nebulosities of HD 148937, NGC 6164/6165 (Westerlund 1961; Catchpole & Feast 1970; Bruhweiler et al. 1981) have been shown to be nitrogen rich and oxygen poor (Leitherer & Chavarría-K. 1987; Dufour, Parker, & Henize 1988); thus, they constitute a further relationship between the Of?p and Ofpe/WN9 classes.

5. SUMMARY

We have discovered large, recurrent spectral variations in the Of?p star HD 191612, between two reproducible, peculiar states. The spectral type changes from O6-O7 in one state to O8 in the other, with correlated changes in unusual emission-line features. These variations are very similar to those well documented in the literature for one of the other two Galactic members of this category, HD 108, and suggested for the other, HD 148937. The spectrum of HD 191612 has been shown to be constant over several consecutive nights, and no significant radial velocity variations have been detected; the spectral variations may occur on long timescales, although partial coverage during 2002 suggests a shorter event. Estimates of the stellar parameters and mass-loss rates in the two states have been derived. There is no observational basis for an explanation of these bizarre phenomena at the present time. Comparisons have been made with various properties of massive binaries, rapid rotators, and quiescent luminous blue variables; however, except for the elimination of short-period, interacting binaries with massive companions, a relationship between the Of?p class and the other categories can be neither established nor ruled out. Further observational work with intensive temporal coverage will be required for progress toward an explanation of the mysterious Of?p stars.

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REFERENCES

Bagnuolo, W. G., Jr., & Barry, D. J. 1996, ApJ, 469, 347
Bagnuolo, W. G., Jr., Gies, D. R., Hahula, M. E., Wiemker, R., & Wiggs, M. S. 1994, ApJ, 423, 446
Bohannan, B., & Conti, P. S. 1976, ApJ, 204, 797
Bohannan, B., & Walborn, N. R. 1989, PASP, 101, 520
Bruhweiler, F. C., Gull, T. R., Henize, K. G., & Cannon, R. D. 1981, ApJ, 251, 126
Catchpole, R. M., & Feast, M. W. 1970, Observatory, 90, 136
Chlebowski, T. 1989, ApJ, 342, 1091
Conti, P. S. 1973, ApJ, 179, 161
Conti, P. S., & Ebbets, D. 1977, ApJ, 213, 438
Conti, P. S., Garmany, C. D., & Hutchings, J. B. 1977, ApJ, 215, 561
Conti, P. S., & Leep, E. M. 1974, ApJ, 193, 113
Corcoran, M. F., Ishibashi, K., Swank, J. H., & Petre, R. 2001, ApJ, 547, 1034
Cowley, A. P., & Hutchings, J. B. 1976, PASP, 88, 456
Crowther, P. A., Hillier, D. J., & Smith, L. J. 1995, A&A, 293, 172
Crowther, P. A., & Smith, L. J. 1997, A&A, 320, 500
Damineli, A., Kaufer, A., Wolf, B., Stahl, O., Lopes, D. F., & de Araújo, F. X. 2000, ApJ, 528, L101
Dufour, R. J., Parker, R. A. R., & Henize, K. G. 1988, ApJ, 327, 859
Herrero, A., Kudritzki, R. P., Vilchez, J. M., Kunze, D., Butler, K., & Haser, S. 1992, A&A, 261, 209
Herrero, A., Puls, J., & Najarro, F. 2002, A&A, 396, 949
Heydari-Malayeri, M., & Melnick, J. 1992, A&A, 258, L13
Howarth, I. D., Siebert, K. W., Hussain, G. A. J., & Prinja, R. K. 1997, MNRAS, 284, 265
Humphreys, R. M. 1978, ApJS, 38, 309
Hutchings, J. B. 1975, PASP, 87, 245
———. 1977, PASP, 89, 668
Hutchings, J. B., & Cowley, A. P. 1976, ApJ, 206, 490
Josephs, T. S., Gies, D. R., Bagnuolo, W. G., Jr., & Shure, M. A. 2001, PASP, 113, 957
Kane, L. G., McKeith, C. D., & Dufton, P. L. 1981, MNRAS, 194, 537
Lamers, H. J. G. L. M., Nota, A., Panagia, N., Smith, L. J., & Langer, N. 2001, ApJ, 551, 764
Leitherer, C., & Chavarría-K., C. 1987, A&A, 175, 208
Massey, P., & Duffy, A. S. 2001, ApJ, 550, 713
Mihalas, D., Hummer, D. G., & Conti, P. S. 1972, ApJ, 175, L99
Monnier, J. D., Tuthill, P. G., & Danchi, W. C. 2002, ApJ, 567, L137
Morgan, W. W., Code, A. D., & Whitford, A. E. 1955, ApJS, 2, 41
Nazé, Y., Vreux, J.-M., & Rauw, G. 2001, A&A, 372, 195
Nota, A., Livio, M., Clampin, M., & Schulte-Ladbeck, R. 1995, ApJ, 448, 788
Nota, A., Pasquali, A., Drissen, L., Leitherer, C., Robert, C., Moffat, A. F. J., & Schmutz, W. 1996, ApJS, 102, 383
Pasquali, A., Langer, N., Schmutz, W., Leitherer, C., Nota, A., Hubeny, I., & Moffat, A. F. J. 1997a, ApJ, 478, 340
Pasquali, A., Nota, A., & Clampin, M. 1999, A&A, 343, 536
Pasquali, A., Schmutz, W., Nota, A., & Origlia, L. 1997b, A&A, 327, 265
Penny, L. R. 1996, ApJ, 463, 737
Peppel, U. 1984, A&AS, 57, 107
Rauw, G., Vreux, J.-M., & Bohannan, B. 1999, ApJ, 517, 416
Roman, N. G. 1951, ApJ, 114, 492
Schmutz, W., Leitherer, C., Hubeny, I., Vogel, M., Hamann, W.-R., & Wessolowski, U. 1991, ApJ, 372, 664
Smith, L. J., Nota, A., Pasquali, A., Leitherer, C., Clampin, M., & Crowther, P. A. 1998, ApJ, 503, 278
Smith, N. 2002, MNRAS, 337, 1252
Smith, N., Gehrz, R. D., Stahl, O., Balick, B., & Kaufer, A. 2002, ApJ, 578, 464
Walborn, N. R. 1971, ApJS, 23, 257
———. 1972a, AJ, 77, 312
———. 1972b, ApJ, 176, L119
———. 1973, AJ, 78, 1067
———. 1977, ApJ, 215, 53
———. 1980, ApJS, 44, 535
———. 1982a, AJ, 87, 1300
———. 1982b, ApJ, 256, 452
———. 2001, in ASP Conf. Ser. 242, Eta Carinae and Other Mysterious Stars, ed. T. R. Gull, S. Johansson, & K. Davidson (San Francisco: ASP), 217
Walborn, N. R., & Fitzpatrick, E. L. 1990, PASP, 102, 379
Walborn, N. R., Lennon, D. J., Heap, S. R., Lindler, D. J., Smith, L. J., Evans, C. J., & Parker, J. Wm. 2000, PASP, 112, 1243
Walborn, N. R., Nichols-Bohlin, J., & Panek, R. J. 1985, *International Ultraviolet Explorer* Atlas of O-Type Spectra from 1200 to 1900 Å (NASA RP 1155; Washington: NASA)
Werner, K., & Rauch, T. 2001, in ASP Conf. Ser. 242, Eta Carinae and Other Mysterious Stars, ed. T. R. Gull, S. Johansson, & K. Davidson (San Francisco: ASP), 229
Westerlund, B. 1961, Ark. Astron., 2, 467
Williams, P. M., van der Hucht, K. A., Pollock, A. M. T., Florkowski, D. R., van der Woerd, H., & Wamsteker, W. M. 1990, MNRAS, 243, 662
Wolf, B., Stahl, O., Smolinski, J., & Cassatella, A. 1988, A&AS, 74, 239