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INTERFEROMETRIC STUDIES OF INTERSTELLAR CALCIUM LINES

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ABSTRACT

Interferometric, photoelectric scans of the interstellar calcium K-lines in the spectra of 65 stars are presented. The scans were obtained with a PEPSIOS spectrometer having a passband with a full half-intensity width of 1.0 km s^{-1} or 0.013 Å. The fivefold improvement in resolution over that used by Adams reveals numerous line components which correspond very well to those of the interstellar sodium lines, apart from frequent differences in relative intensities.

I. INTRODUCTION

The H- and K-lines of Ca II are the most extensively observed and, in general, the second strongest of the familiar optical interstellar absorption lines. In addition to their fundamental importance in delineating the spatial and kinematic distribution of the local interstellar gas, it has long been recognized that such lines convey other important information about the absorbing gas, especially when they are compared with other interstellar lines such as the sodium D-lines or the hydrogen 21-cm lines (Routly and Spitzer 1952; Münch 1968; Herbig 1968; Habing 1969; Hobbs 1971). For example, the relative strengths of the calcium and sodium lines formed in a given cloud probably yield for that cloud an admixture of information about, primarily, the Ca/Na abundance ratio in the cloud and the interstellar radiation field to which it is exposed. The typical Ca/Na abundances so derived still cannot be reconciled easily with theoretical predictions; these abundances affect our present ideas about the cooling of the interstellar gas and the formation of interstellar grains (Spitzer 1968; Field, Goldsmith, and Habing 1969). The other factor, the interstellar radiation field, influences the relative line strengths in a particularly useful way, in that the photoionization thresholds for Ca II and Na I occur at 1042 and 2312 Å, respectively. Thus, the comparatively easily determined strengths of the optical absorption lines may measure, in effect, an important color index for the far-ultraviolet part of the incident radiation field.

Modern instrumentation allows under practical conditions a highly desirable improvement in spectral resolution, by a factor between 5 and 10 over that used by Adams (1949) in his extensive survey of the interstellar H- and K-lines. Interferometric, photoelectric line profiles of this kind have already been obtained for a substantial number of interstellar sodium D-lines (Hobbs 1969*a*), and radio observations of the appropriate hydrogen 21-cm lines also have been extended recently in quality and number (Goldstein and MacDonald 1969). Comparable new observations therefore seem important for the H- and K-lines, especially since it is specifically their strengths and the derived Ca/H abundance ratio which appear to be anomalous; both remain conspicuously too small for easy interpretation (Herbig 1968; Habing 1969). The measurements reported here yield profiles of the interstellar K-line in the spectra of 65 stars, obtained with a passband having a full half-intensity width (FWHM) of about 0.013 Å or 1.0 km s^{-1}, or a resolving power of about 330,000.

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II. OBSERVATIONS

The observations were obtained between 1970 May and 1971 February, using the PEPSIOS spectrometer of the Yerkes Observatory at the coudé focus of the 107-inch (272 cm) telescope at the McDonald Observatory. The general features of both the spectrometer and the observational procedure were very similar to those described in detail for the earlier sodium observations (Hobbs 1969*a*), except that a conventional two-channel pulse-counting system replaced d.c. detection in recording the data. As described next, different choices were made for several of the important instrumental parameters in the present program, however.

The three optically contacted Fabry-Perot spacers were in approximately the McNutt (1965) ratios, the longest being 2.0 mm in length. Dielectric coatings with 91 percent reflectivity and a reflective finesse $N_R = 33$ were ordered, which would have given a passband width of about 0.010 Å or 0.76 km s^{-1}, when the broadening effects of the entrance aperture are included. The choice of this velocity resolution, somewhat poorer than that used for the D-lines, was based on the sodium profiles. Those scans suggested that exchanging some resolution for higher signal levels would be advantageous. (Note also the absence of hyperfine structure for the ^{40}Ca isotope.) The coatings actually received and used were rather unsatisfactory with regard to both reflectivity and flatness. One consequence of both of these deficiencies was the unexpectedly broad passband of 1.0 km s^{-1} noted above. This theoretically estimated passband was approximately confirmed in actual scans of both the narrow K-lines from laboratory hollow-cathode lamps and the narrowest interstellar K-lines. The useful Fabry-Perot aperture selected by an iris diaphragm was always 25 mm in diameter, and the diameter of the circular entrance aperture then corresponded to 7″ on the sky.

A consequence of the poor coatings which was much more important than the poorer resolution was the greatly increased amount of parasitic light transmitted in the extended wings of the instrumental profile. This contribution comprised fully 65 percent of all the light transmitted at a continuum point in the scans, in contrast to 6 percent in the sodium program. Its principal effect was to increase substantially the noise in the scans, since subtraction of this constant (in relative amount) but large background from the scans still leaves its statistical fluctuations present in the resulting spectrum. These random errors were the largest ones present in all of the scans. On the other hand, no consequent systematic errors of significance were expected or found. Consider, for example, the "constant" parasitic-light fraction of 65 percent, used everywhere in the data reduction. This fraction cannot in fact be independent of spectral type, owing to changes with spectral type in both the shape of the continuum energy distribution and the line spectrum. However, laboratory measurements with dye filters showed that, as a result of the 12 Å (FWHM) interference filter used as a premonochromator, most of the parasitic light was transmitted within ± 25 Å of the K-line. Furthermore, the presence of a stellar K-line independently restricted the spectral types essentially to O and B, a fairly narrow range of spectral types in the present context. As a result, the ratios of our equivalent widths to those obtained from Adams's material (Spitzer, Epstein, and Li Hen 1950) show no systematic deviation from unity, when plotted against spectral type. To verify that the parasitic-light fraction did not change with time either, scans of a few program stars were obtained over nearly the entire observing period. These repeated scans showed excellent reproducibility, both before and after subtraction of the parasitic light.

The large increase in the parasitic-light fraction follows basically from the very sensitive dependence of this quantity upon the coating reflectivities. Small deficiencies in the latter greatly enhance the effects of the slight overlaps among the mutually offset side orders of the three individual transmission functions. In quantitative terms, McNutt

(1965) showed that the parasitic-light fraction varies as approximately the fifth power of the finesse, which itself depends sensitively on the reflectivity. For example, a 3 percent change in the reflectivity R from 0.91 to 0.88 changes the pertinent quantity N_R^5 governing the parasitic light by a factor of about 5, since $N_R = \pi R^{1/2}/(1 - R)$. Such measured reflectivity deficiencies in the coatings used account well for the observed parasitic-light fraction, and simultaneously exclude directly any substantial contribution from possible microscopic pinholes in the coatings.

No useful laboratory absorption cell was available within the scan range delimited by the interference filter. To measure directly the parasitic-light fraction, we relied instead upon a few interstellar clouds with presumed large central optical depths (see especially λ Cep and 1 Cas; also κ Cas and 55 Cyg), as facsimiles of such a laboratory cell. An upper limit to the parasitic light followed from requiring that the residual intensities be nonnegative. A lower limit was obtained by assuming that the central intensities were very small, based on the large equivalent widths measured previously for these K-lines and on the very strong saturation of the corresponding D_1 and D_2 lines. In addition, a second, independent method was also used to estimate the parasitic-light fraction. Since each different choice made for this parameter establishes the true zeros of intensity at a different fixed fraction of the continuum levels in the raw scans, each gives a different set of resulting equivalent widths. A comparison of a number of such sets of equivalent widths with those of Spitzer *et al.* (1950) for a large number of common stars yielded an estimated parasitic-light fraction which agreed with the former estimate to within 3 percent. A net uncertainty of about 2 percent remained in the parasitic-light fraction, after the two independent constraints were considered together, which allows a systematic error of up to 5 percent in locating the true zero of intensity in the corrected scans.

The 65 stars observed are listed in table 1. Of these, 53 were observed by Adams (1949) and 3 by Münch (1957), at lower resolution. The entries adopted in table 1 for the 60 stars which were also observed in the earlier sodium program are taken from Hobbs (1969*a*), with similar but new entries for the additional 5 stars (γ Cas, γ Ori, o^2 CMa, η Leo, λ Cep). A number of new unpublished MK spectral types were kindly provided by Dr. N. Walborn. No scans of the H line were included, for the following three reasons: most of the K-lines were expected to be weak enough for the effects of line saturation not to be extremely large, no telluric lines affect the region of the K-line, and the high parasitic-light level increased the required observation time.

For a prespecified integration time per resolution element, the present scans proved to be somewhat noisier than the corresponding sodium scans, owing to (1) the slightly lower absolute counting rate in the signal channel (after subtraction of the parasitic light), despite the broader passband, and (2) the high parasitic-light counting rate. The first factor resulted primarily from the shorter wavelength. The improved quantum efficiency of the photomultiplier in the near-ultraviolet was more than offset by the enhanced importance of the imperfections in the coated Fabry-Perot plates, the increased absorption in the dielectric coatings, and the reduced transmission of the interference filter. Of these effects, the poor flatness characteristics of the coatings used made the first effect unexpectedly and unnecessarily serious. The net result was that slightly longer observing times were required to achieve the same precisions as those in the sodium program.

III. DATA

The corrected line profiles are presented in figure 1, where all of the profiles are averages of three or more scans. The small triangular marks on the velocity axes give the zero points for velocities measured with respect to the local standard of rest, based on a solar motion of 20 km s^{-1} toward $\alpha(1900) = 18^h$ and $\delta(1900) = 30°$. The empirical probable errors in the ordinates of the scans range from about 1 percent in the con-

TABLE I

THE STARS OBSERVED

STAR	l^{II}(1900)	b^{II}(1900)	V	Sp	R.V. (km/sec)	E(B-V)	d(pc)
κ Cas	120°50'	00°08'	4.15	B0.7Ia	-02v	0.34	900
ο Cas	121 46	-14 35	4.50	B2V	-08	0.18	200
ν And	122 36	-21 48	4.53	B5V	-24v	0.01	130
γ Cas	123 34	-02 09	2.2v	B0.5IVpe	-07	0.20	210
φ Per	131 19	-11 20	4.03	B1III-Vpe	- 01v	0.22	300
ψ Per	149 10	-06 06	4.21	B5e	0	0.10	170
δ Per	150 17	-05 47	2.99	B5III	-09v	0.04	130
ο Per	160 22	-17 45	3.82	B1III	19v	0.32	360
17 Tau	166 10	-23 51	3.69	B6III	12	0.03	120
19 Tau	165 59	-23 33	4.29	B6V	06	0.03	120
20 Tau	166 10	-23 32	3.86	B7III	08	0.05	120
23 Tau	166 34	-23 46	4.16	B6IVnn	06	0.08	120
η Tau	166 40	-23 28	2.86	B7III	10	0.03	120
27 Tau	167 00	-23 15	3.62	B8III	09	0.01	120
ζ Per	162 17	-16 42	2.83	B1Ib	21	0.32	360
ε Per	157 21	-10 06	2.88	B0.7III	-01v	0.11	210
ξ Per	160 22	-13 07	4.03	O7.5III(n(f))	70v	0.33	700
π^4 Ori	192 53	-23 32	3.69	B2III	23v	0.07	450
β Ori	209 14	-25 15	0.08	B8Ia	21v	0.00	450
η Ori	204 52	-20 24	3.35	B0.5V	20v	0.11	450
γ Ori	196 55	-15 58	1.64	B2III	18	0.01	110
δ Ori	203 51	-17 45	2.20	O9.5II	16v	0.09	450
ι Ori	209 32	-19 36	2.77	O9III	22v	0.06	450
ε Ori	205 13	-17 15	1.70	B0Ia	26	0.05	450
ζ Tau	185 41	-05 39	2.99	B2IVp	24v	0.05	170
σ Ori	206 49	-17 20	3.75	O9.5V	29v	0.06	450
ζ Ori	206 27	-16 36	1.74	O9.7Ib	18	0.06	450
κ Ori	214 31	-18 30	2.04	B0.5Ia	21	0.04	450
o^2 CMa	235 33	-08 14	3.04	B3Ia	48	0.05	870
η CMa	242 36	-06 29	2.40	B5Ia	41	0.00	760
η Leo	219 31	50 45	3.48	A0Ib	03	0.02	500
ρ Leo	234 53	52 46	3.85	B1Ib	42	0.05	760
π Sco	347 12	20 14	2.88	B1IV	-03v	0.07	170
δ Sco	350 06	22 30	2.32	B0V	-14v	0.19	170
β^1 Sco	353 11	23 37	2.63	B0V	-07v	0.21	170
ω^1 Sco	352 45	22 47	3.95	B1V	-04	0.22	170
σ Sco	351 19	17 01	2.9v	B1III	0v	0.40	170
τ Sco	351 31	12 49	2.82	B0.2V	-01	0.05	170
ζ Oph	06 17	23 36	2.56	O9.5V	-19v	0.32	170
α Oph	35 54	22 35	2.08	A5III	13v	0.00	20
μ Oph	17 00	12 21	4.62	B8III	-19	0.20	140
67 Oph	29 43	12 38	3.97	B5Ib	-04	0.11	740
102 Her	47 25	18 26	4.35	B2V	-15	0.09	210
β Lyr	63 11	14 47	3.42	B pe	-19v	$\leq$0.3	
1 Vul	54 44	04 25	4.25	B3IV	-17	0.16	180
υ Sgr	21 50	-13 46	4.58	A pe	09v	$\leq$0.1	
δ Cyg	78 42	10 15	2.92	B9.5III	-21	0.00	50
ω^1 Cyg	86 04	05 45	4.95	B2V	-22	0.13	260
α Cyg	84 17	02 00	1.26	A2Ia	-05v	0.09	500
λ Cyg	78 05	-04 20	4.54	B5V	-23	0.05	150

TABLE I (cont.)

THE STARS OBSERVED

STAR	l^{II}(1900)	b^{II}(1900)	V	Sp	R.V. (km/sec)	E(B-V)	d(pc)
55 Cyg	85 45	01 30	4.83	B2.5Ia	-07	0.55	1000
57 Cyg	84 54	00 11	4.72	B5V	-20v	0.02	140
σ Cyg	84 12	-06 52	4.24	B9Iab	-04v	0.13	1200
υ Cyg	80 59	-10 03	4.45	B2Ve	04	0.14	210
π^2 Cyg	94 50	-03 13	4.21	B2.5III	-12v	0.07	240
ο Aqr	57 26	-42 40	4.69	B8Ve	-12	0.04	90
λ Cep	103 49	02 36	5.04	O6I(n)f	-74	0.57	670
32 Peg	87 01	-25 53	4.85	B8III	08	0.09	170
2 Lac	97 47	-08 52	4.57	B6IV	-10v	0.04	150
π Aqr	65 59	-44 44	4.86	B1Vpe	04v	0.22	370
6 Lac	97 22	-12 38	4.48	B2IV	-08	0.15	380
10 Lac	96 39	-16 59	4.88	O9V	-10	0.11	600
ο And	102 12	-16 06	3.6v	B6IIIp	-14v	0.04	150
β Psc	78 47	-49 36	4.52	B5Ve	00	0.03	120
1 Cas	109 57	00 47	4.87	B0.5III	-09	0.25	530

tinuum intensity for the brightest stars to about 6 percent for a few of the faintest stars; in addition, a possible systematic error of up to 5 percent in locating the true zero of intensity was noted above. An empirical probable error of between 0.1 and 0.2 km s^{-1} in the abscissae was determined by comparing, for a few stars, many scans taken over a period of several months. An additional systematic error of about the same magnitude is possible in the zero point of the velocity scales, as a result of the width of the laboratory comparison line and of the different illumination of the entrance aperture by the stars and the comparison lamp.

Where stellar K-lines appear to be present, the ordinates of the interpolated stellar spectra are estimated arbitrarily by dotted lines in figure 1. In the presence of an appreciable stellar line, all of the intensities are uncertain to within a multiplicative constant, since a quite extended scan usually would have been required to reach the true stellar continuum. The presence of several closely spaced interstellar lines can also make the interpolation uncertain in the region of those lines. Ten stellar K-lines are explicitly indicated in figure 1. All but one (o^2 CMa, B3 Ia) occur in stars of spectral type B5 or later if supergiants, and B7 or later if of lower luminosity. The radial velocities obtained from all but one (η CMa) of these stellar lines are consistent with published values. On the other hand, broad stellar lines may easily be present but not evident, over some of the shorter scan ranges chosen here. Among 10 stars of spectral type B8 or later, six having short ranges do not show evidence of a presumably broad, shallow stellar line. Still another possibility of this kind is illustrated by ρ Leo (B1 Ib), where the lines scanned here are superposed on an additional broad, shallow feature (Münch 1952), possibly itself of interstellar origin.

The observed lines, indicated in figure 1 by short vertical bars at the continuum levels, carry a numerical coding identical to that used earlier for the sodium scans, although the absence of telluric lines renders the coding essentially superfluous here. Components are labeled 1, 2, or 3 accordingly as they appear single, possibly multiple, or multiple. We have generally been cautious in identifying weak line components; a number of such small continuum variations not labeled in figure 1 may be real.

To the precision possible in comparing figure 1 with Adams's results, the agreement between the two sets of data is generally very good. There is no systematic difference in the velocities obtained, after the required 1.7 km s^{-1} is added to the earlier values. With a few exceptions, the intensities of the line components also accord well, if a probable error of slightly more than 1 class is allowed in Adams's visual intensities.

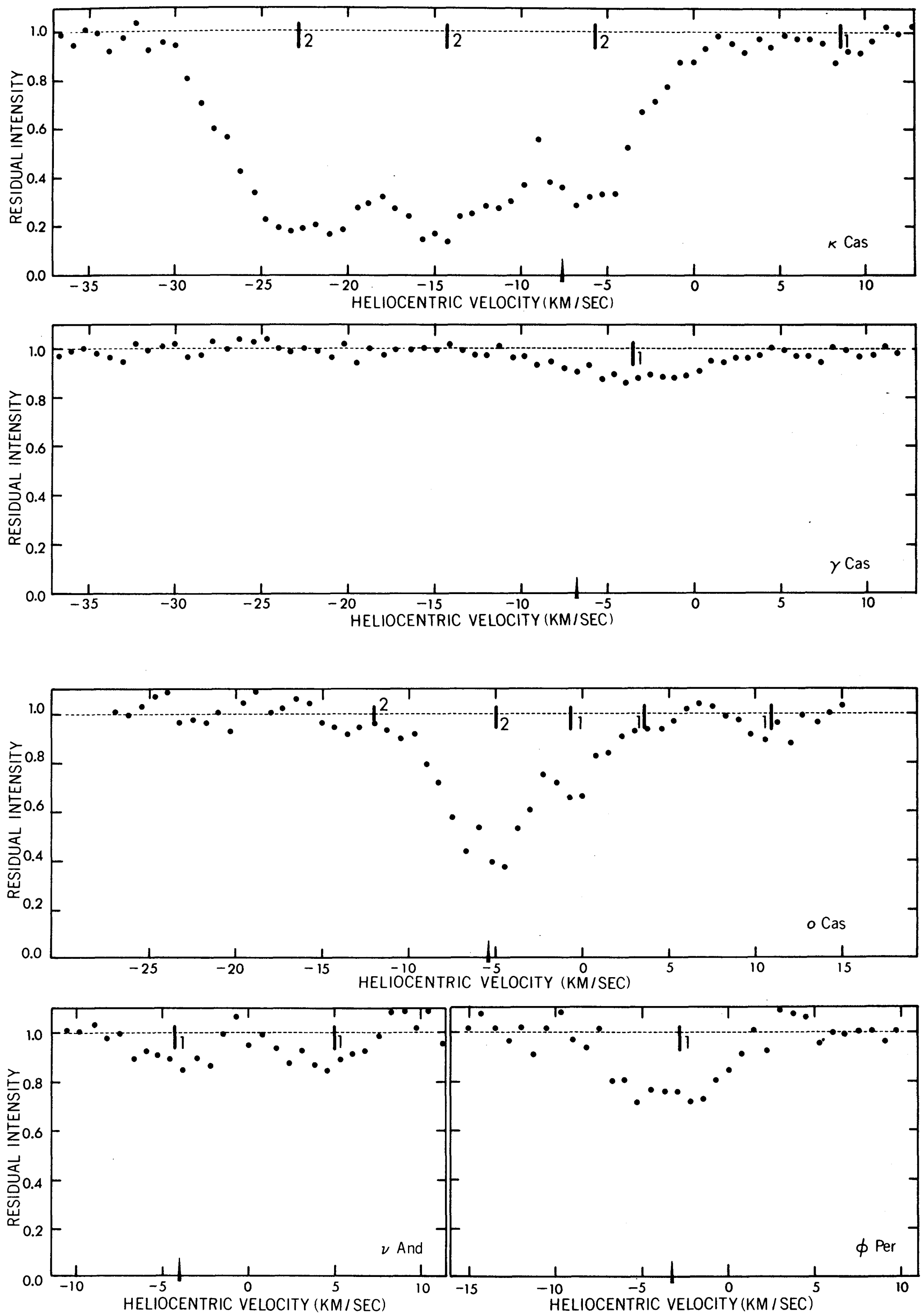

FIG. 1.—The interstellar K-line in the spectra of 65 stars

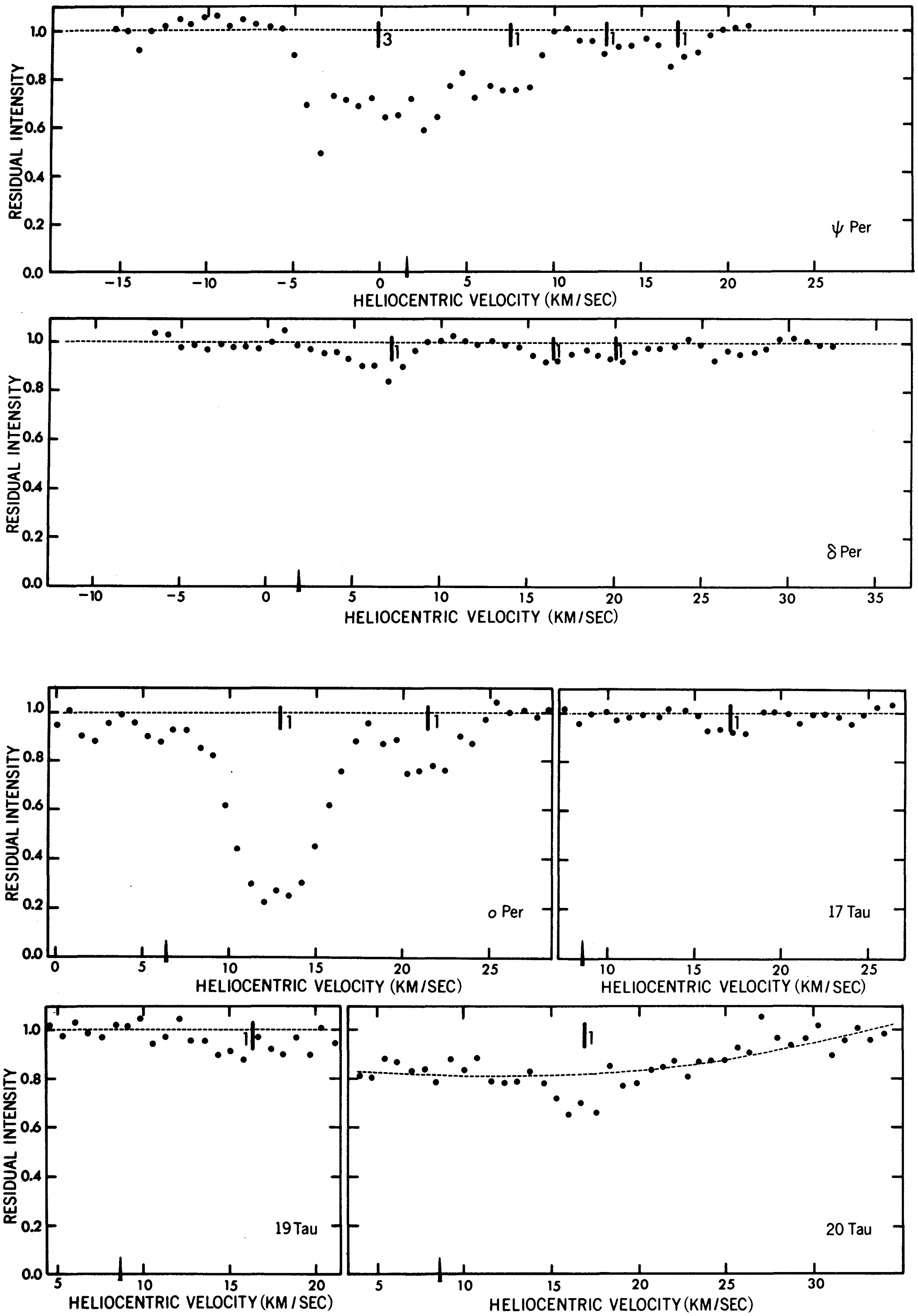

Fig. 1.—*Continued*

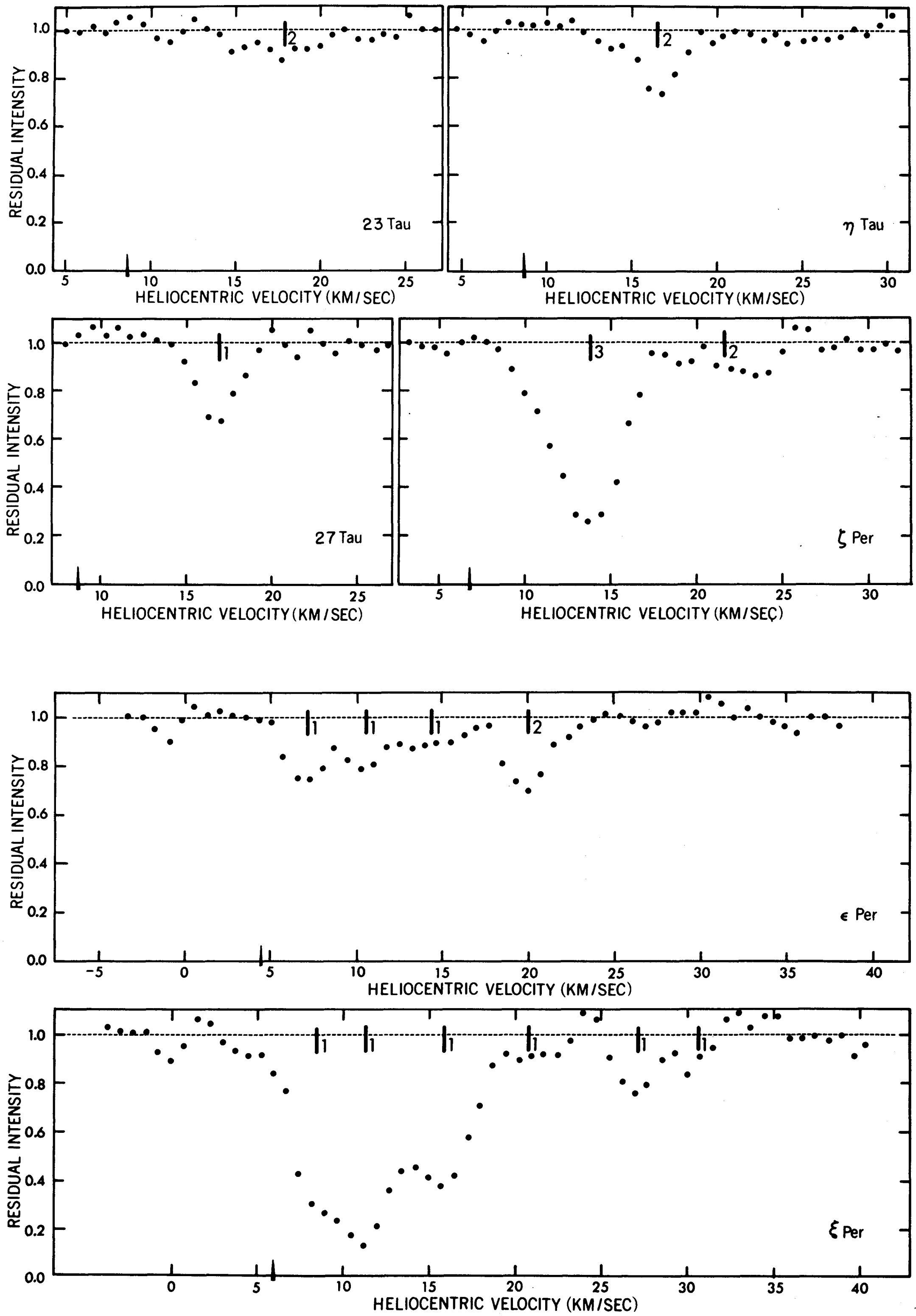

FIG. 1.—*Continued*

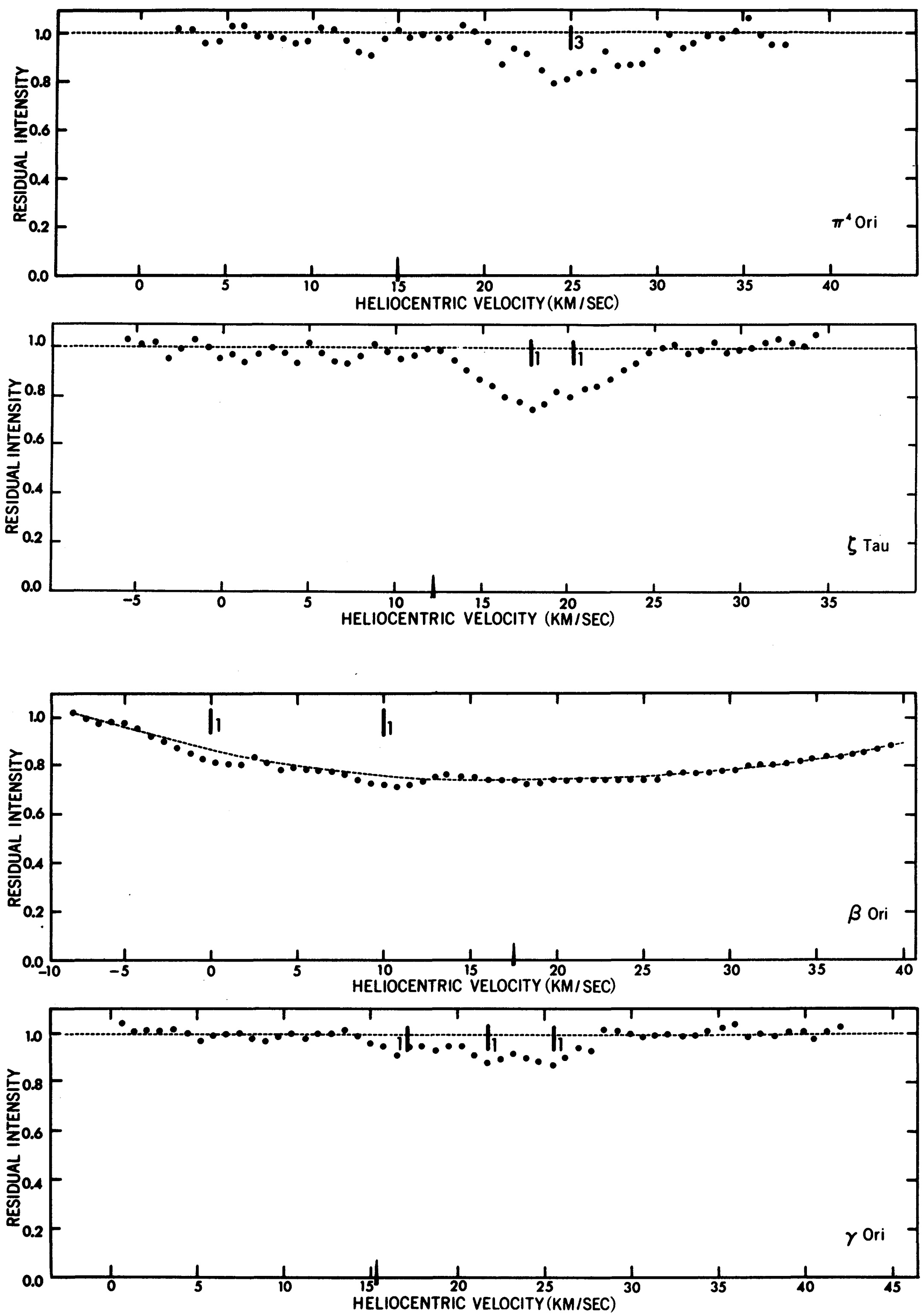

FIG. 1.—*Continued*

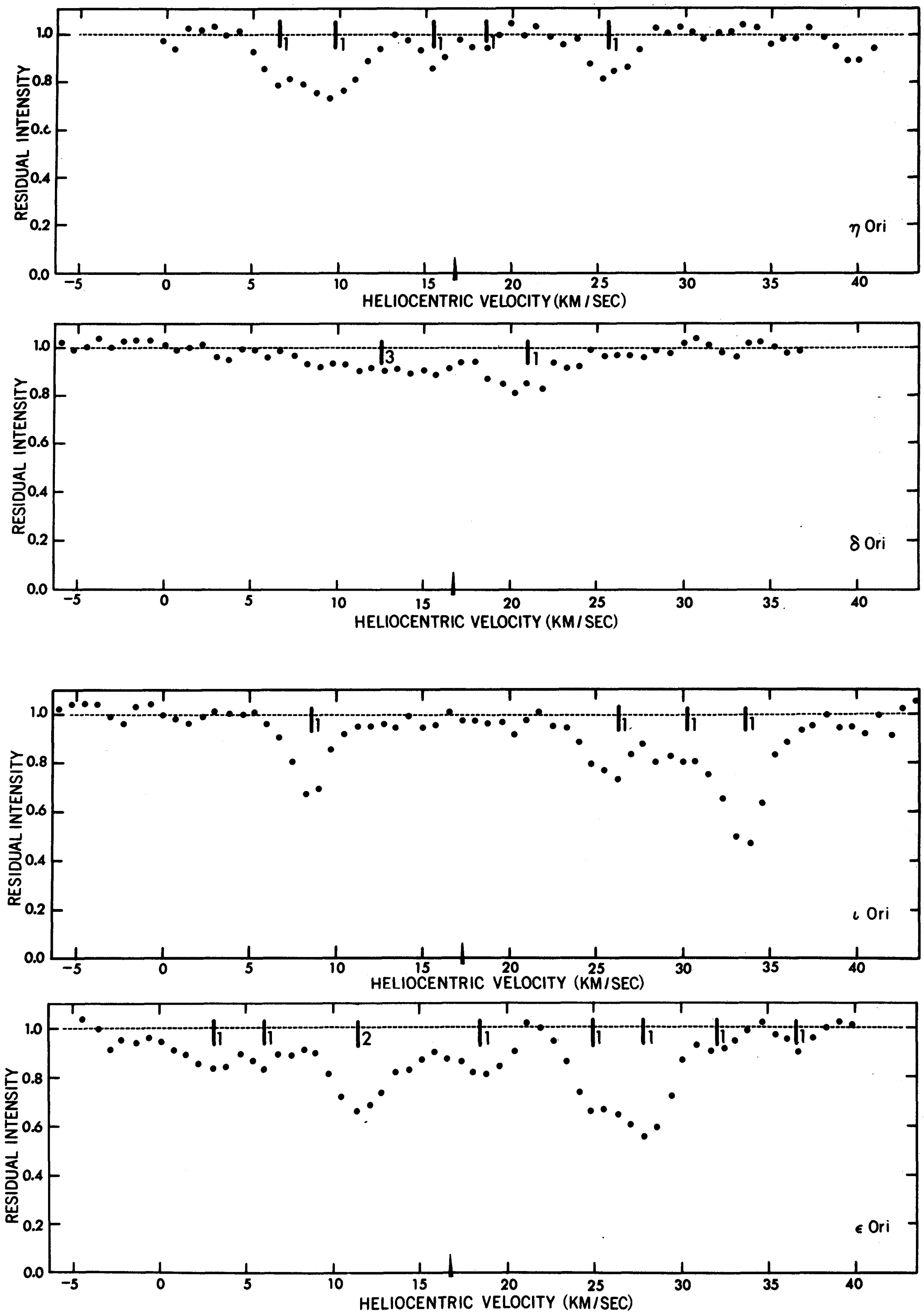

FIG. 1.—*Continued*

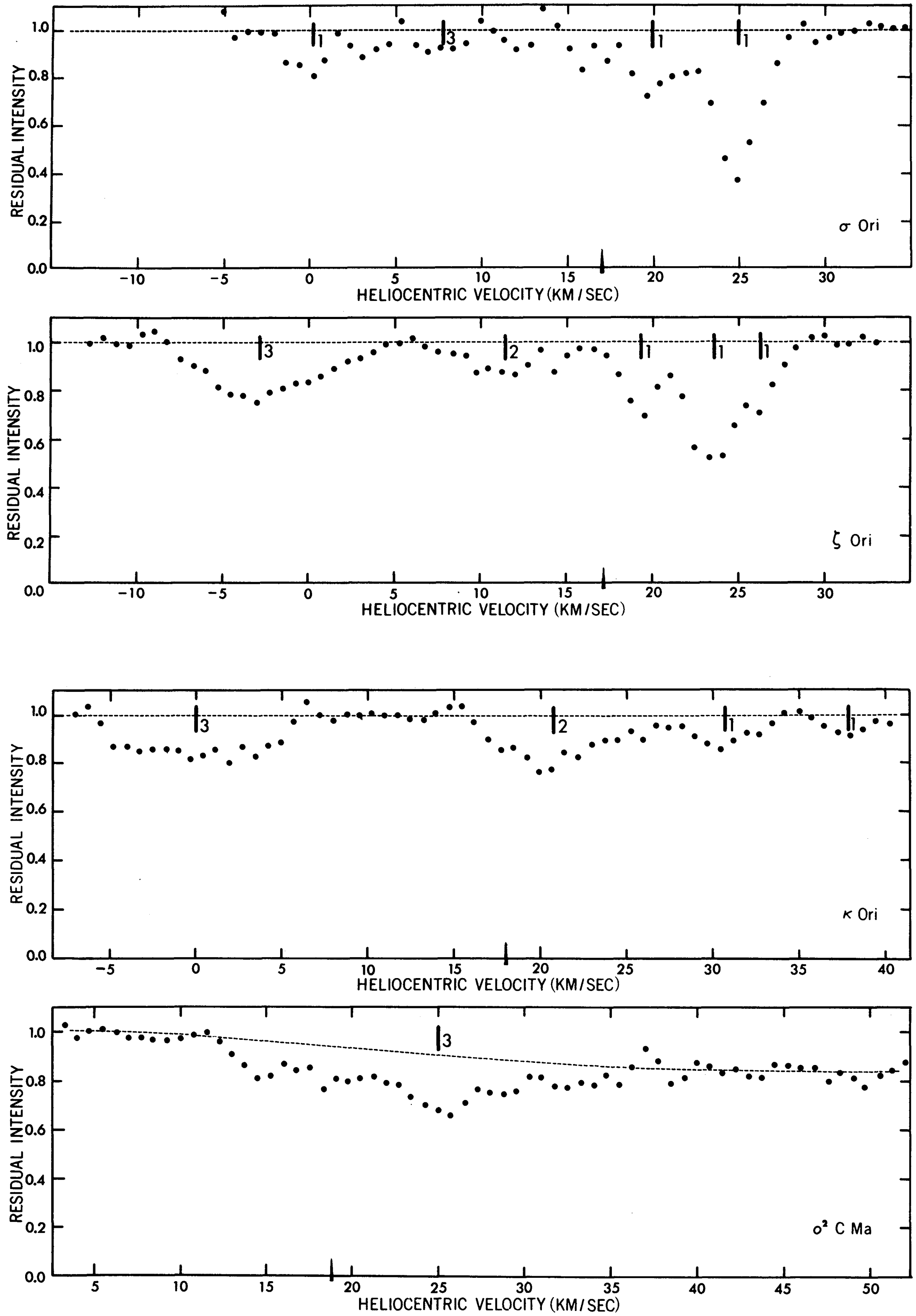

FIG. 1.—*Continued*

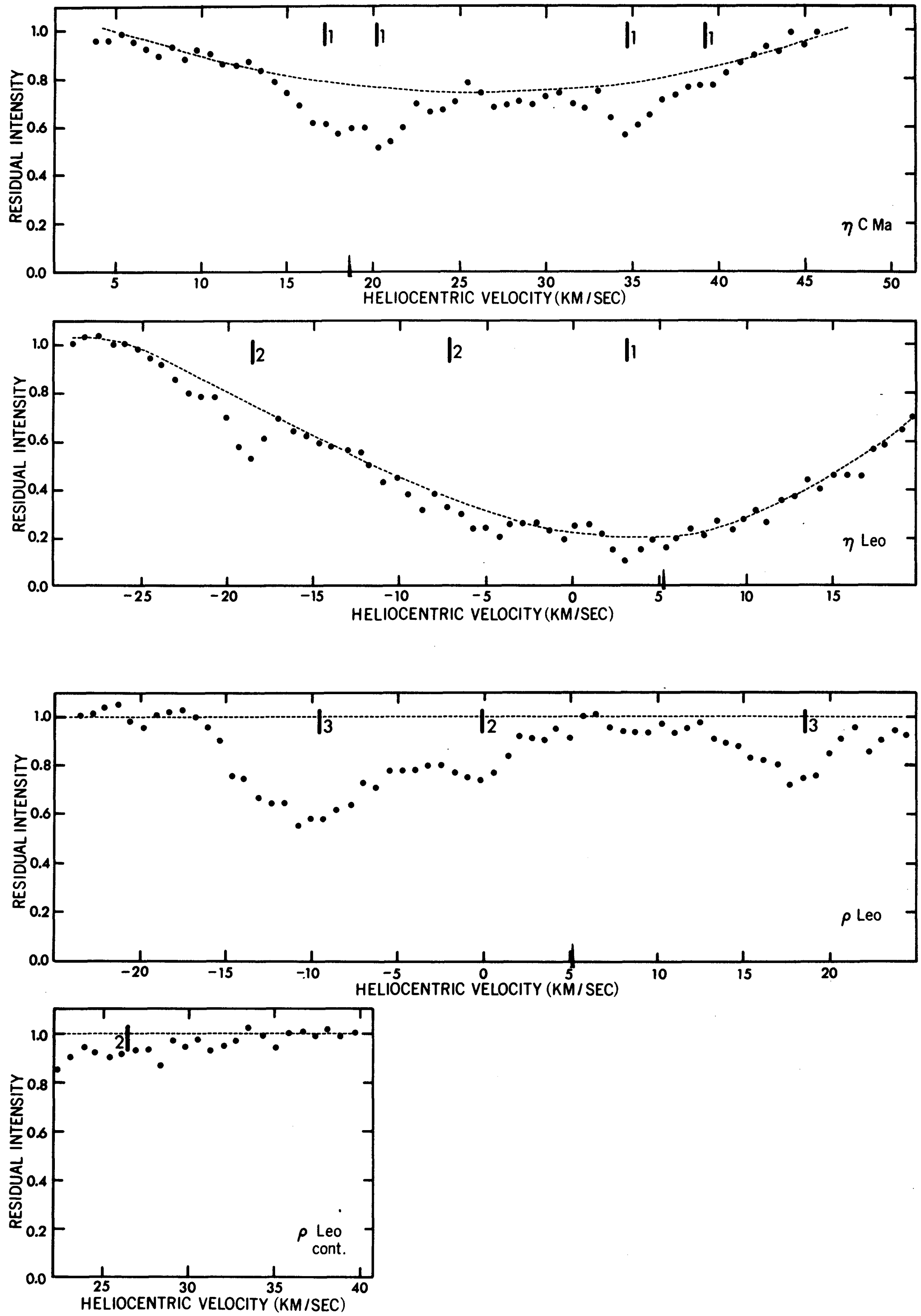

FIG. 1.—*Continued*

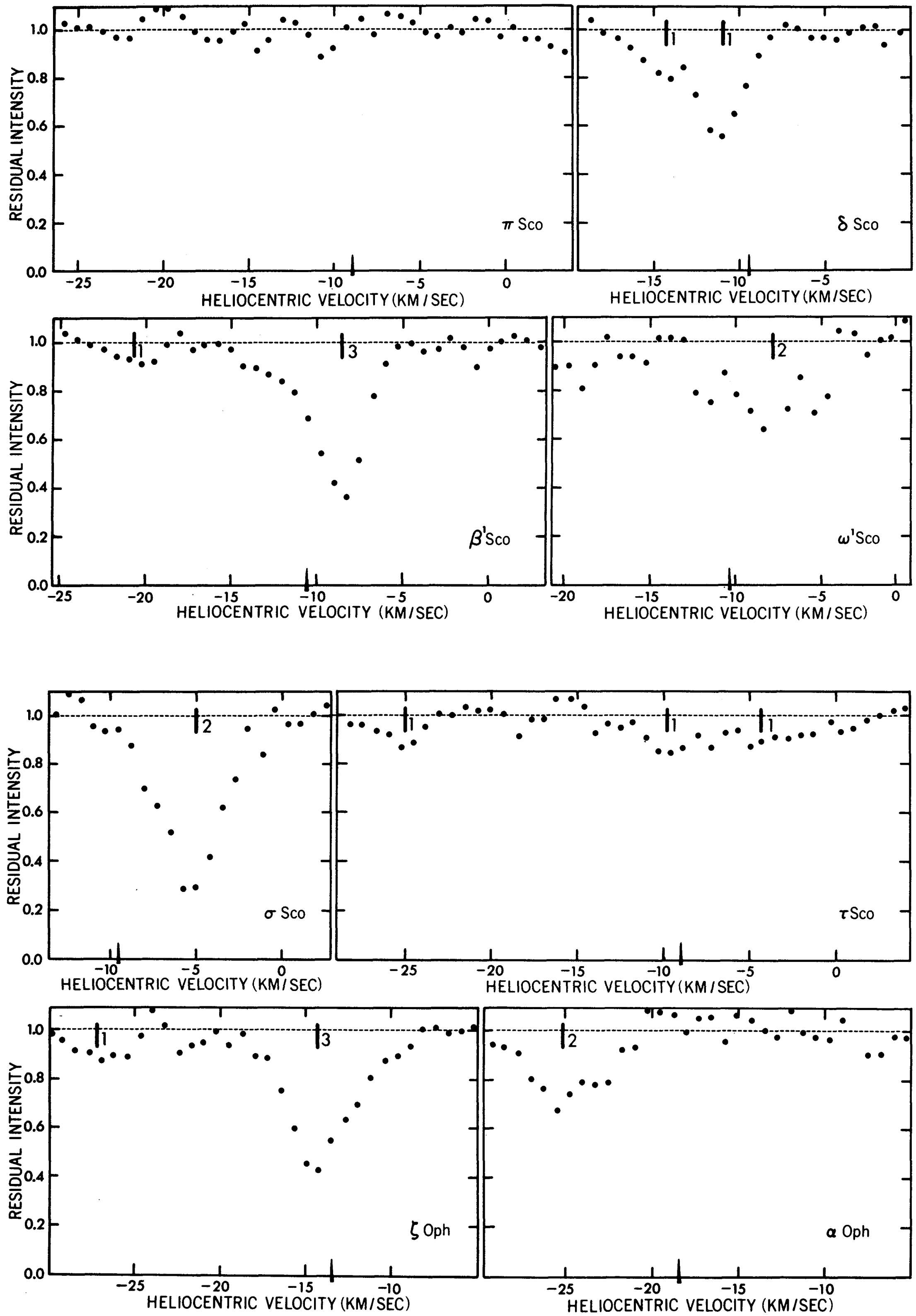

FIG. 1.—*Continued*

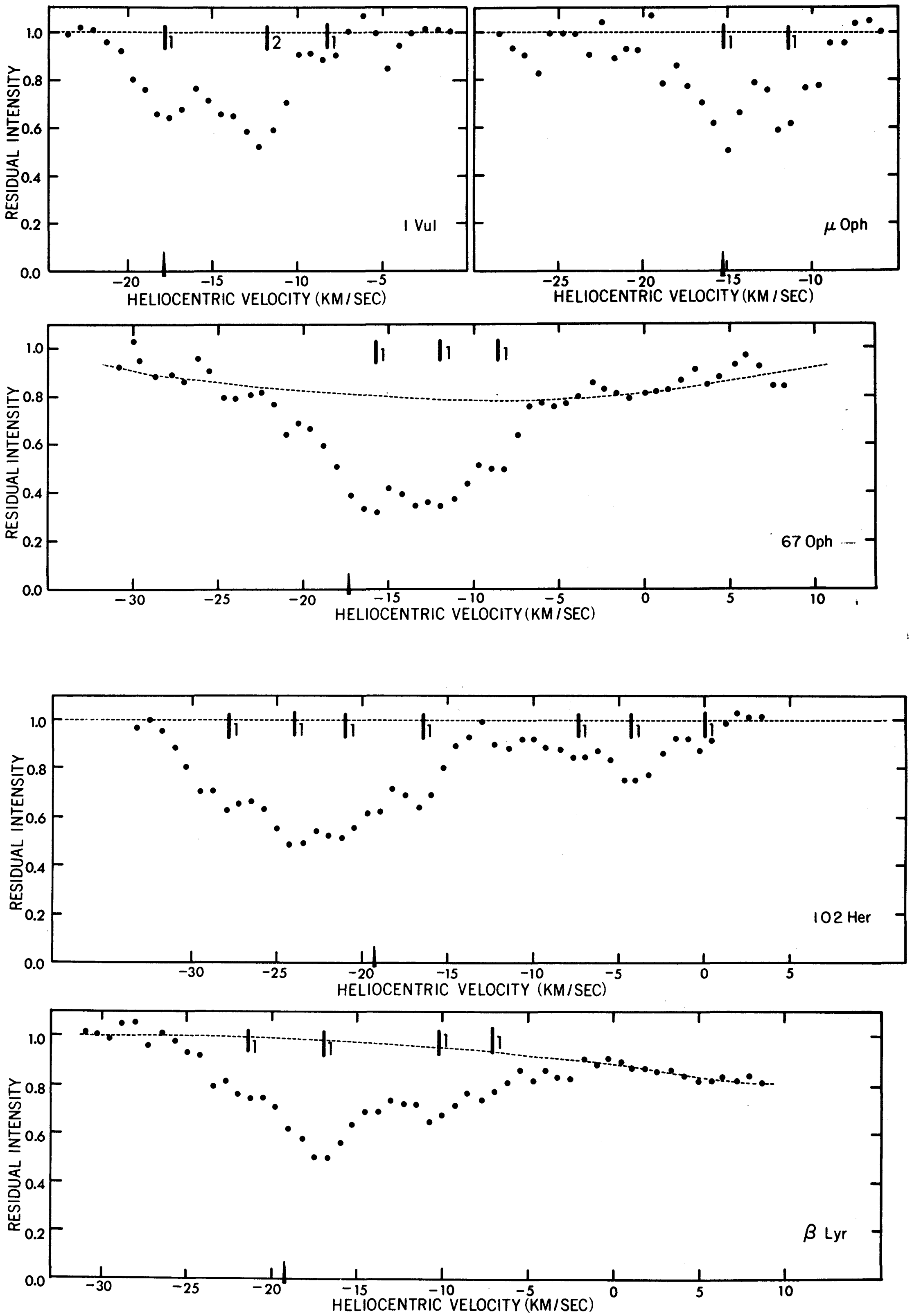

FIG. 1.—*Continued*

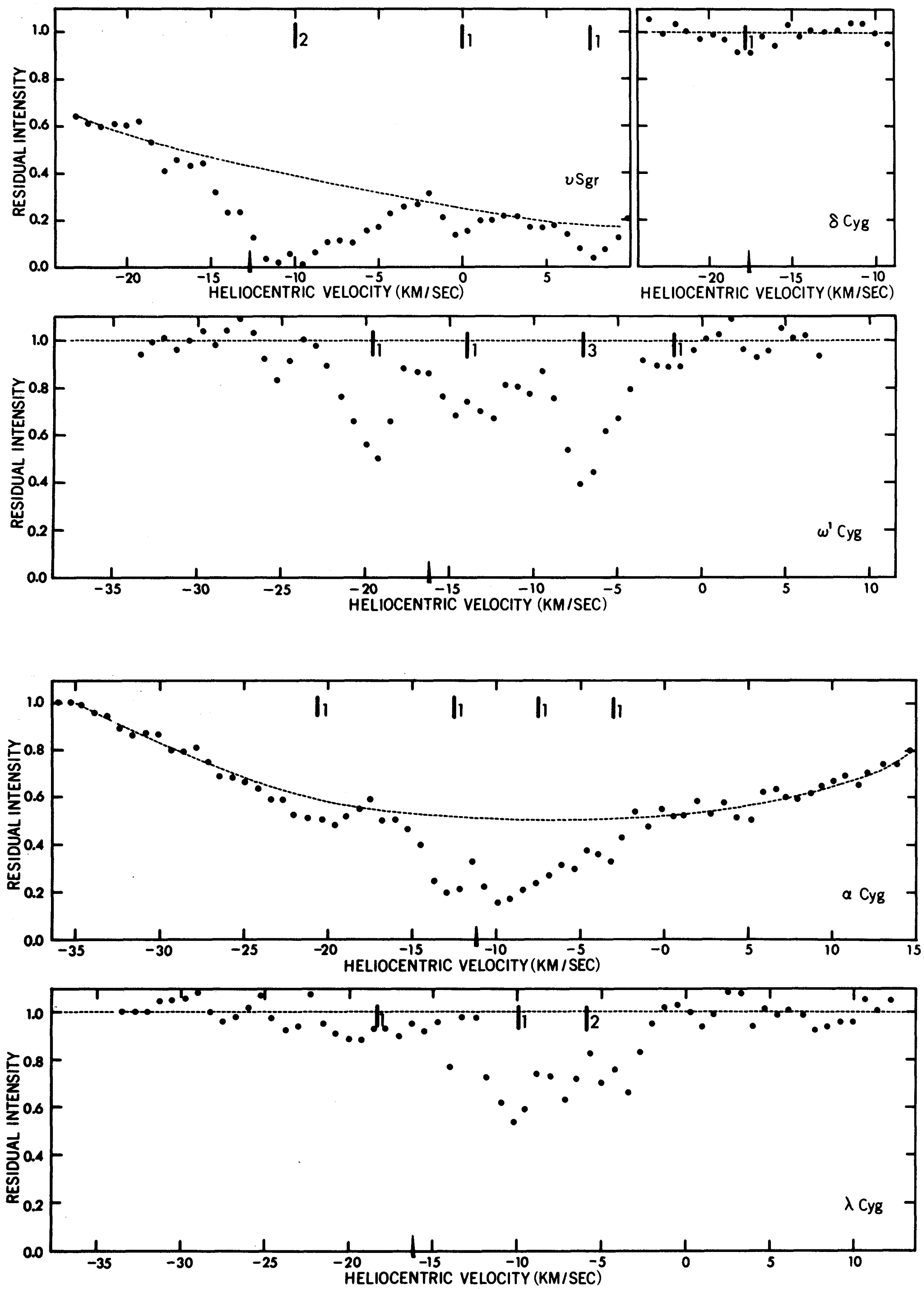

FIG. 1.—*Continued*

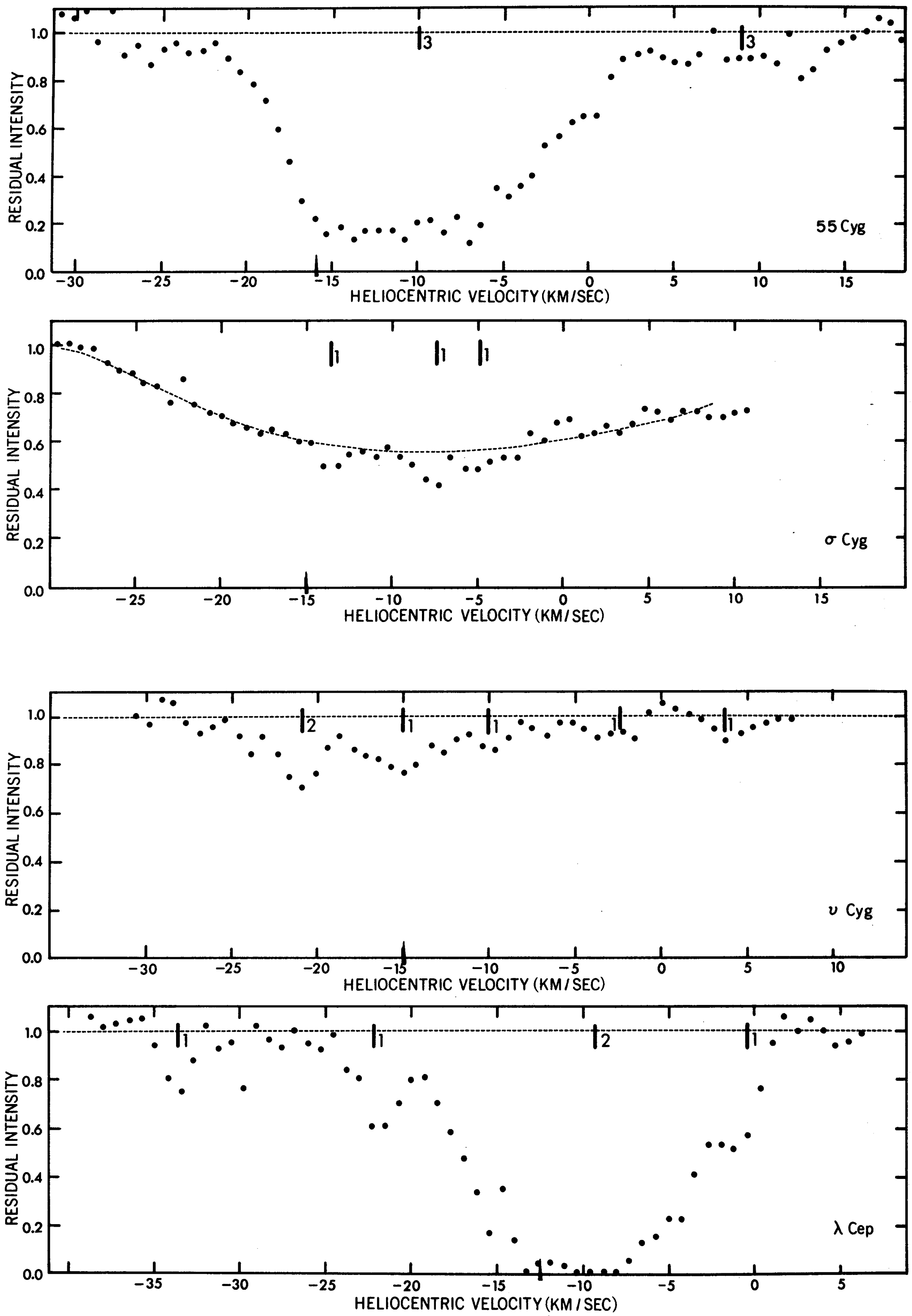

FIG. 1.—*Continued*

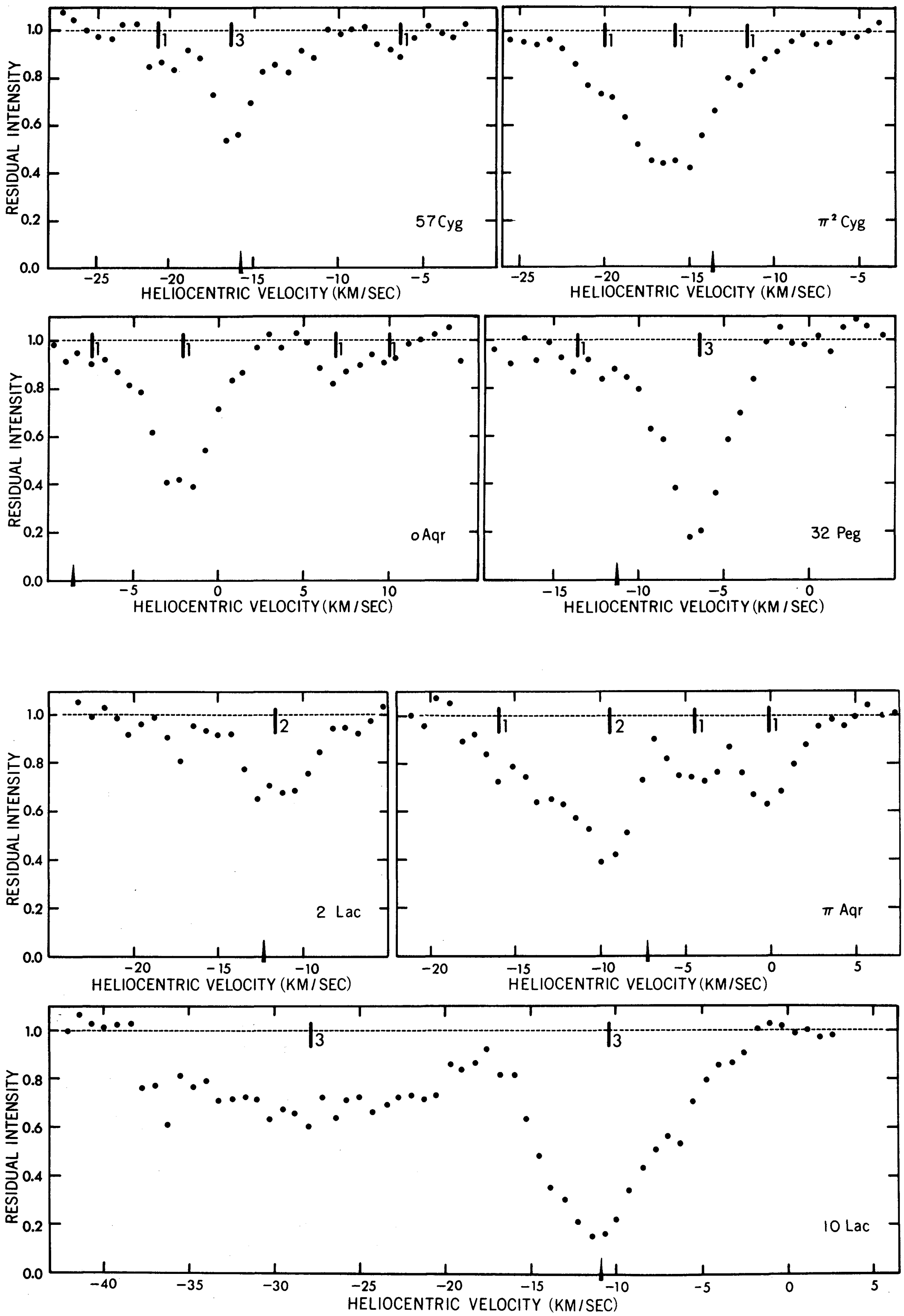

FIG. 1.—*Continued*

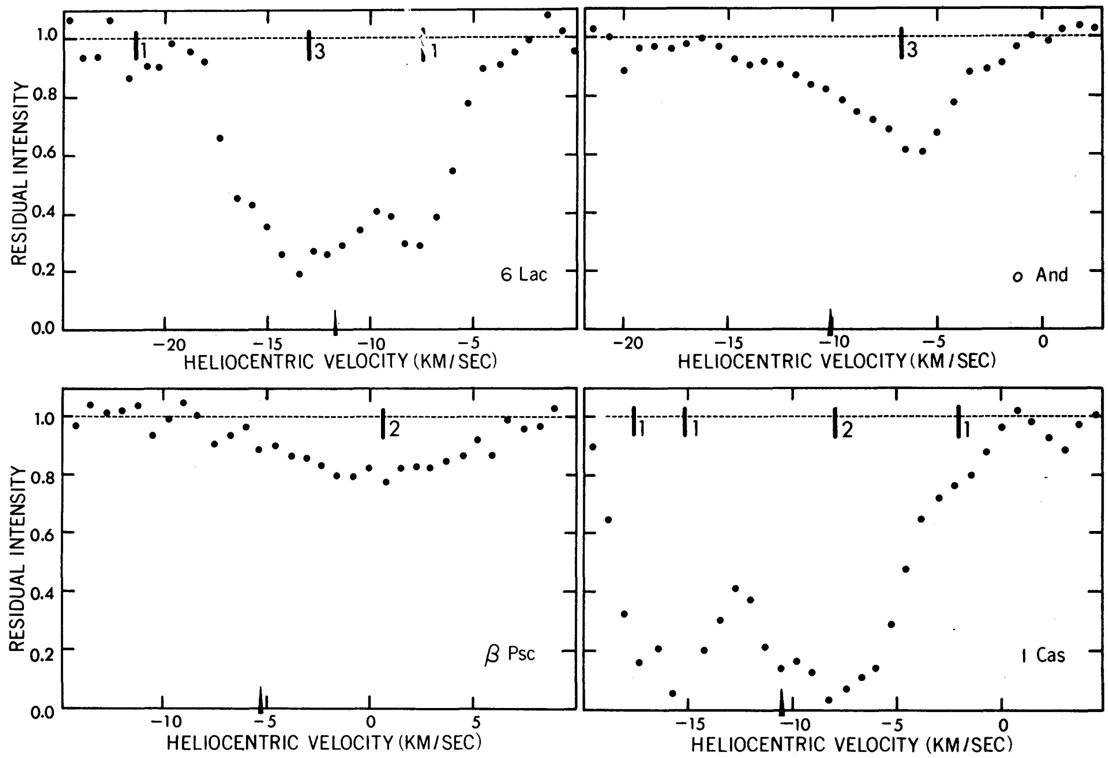

FIG. 1.—*Continued*

Adams's estimates of line intensities are very much larger than ours for π^4 Ori, η CMa, 67 Oph, and α Cyg. In all but the first, substantial stellar lines seem to be present and may explain the discrepancies.

Analyses of the profiles in figure 1 will be given in a subsequent paper, but a few general remarks are appropriate here. The principal characteristics of the scans are easily seen. Most of the lines found by Adams to be single at lower resolution are in fact multiple. Also, although the calcium lines are weaker, the velocities of calcium-line components correspond in almost every case to the interferometric sodium-line components, with no systematic difference between these two sets of velocities. However, in a number of stars the relative strengths of adjacent components are reversed in the two cases (Routly and Spitzer 1952), which could have suggested velocity shifts at lower dispersions.

As has long been recognized, the calcium lines are weaker than the sodium lines, although conventional theory predicts just the opposite. In figure 2 the sodium and calcium lines are compared for five Orion stars, to illustrate the differences. It is noteworthy that the weaker calcium lines frequently begin to show structure which is lost in their sodium counterparts owing to strong saturation (not illustrated in fig. 2). Another advantage of the weaker lines is that the resulting profiles and equivalent widths are less affected by the possible systematic error in the parasitic-light correction discussed in § II. Less saturated lines also yield more accurate column densities.

Finally, one of the measured profiles deserves specific emphasis. The scan of the foreground star γ Ori reveals substantial absorption in the velocity range within which somewhat stronger absorption generally occurs for the more distant stars of the Orion associations (Hobbs 1969*b*). A substantial portion of the gas along the line of sight to the latter stars thus appears to be local and unrelated to the association regions themselves.

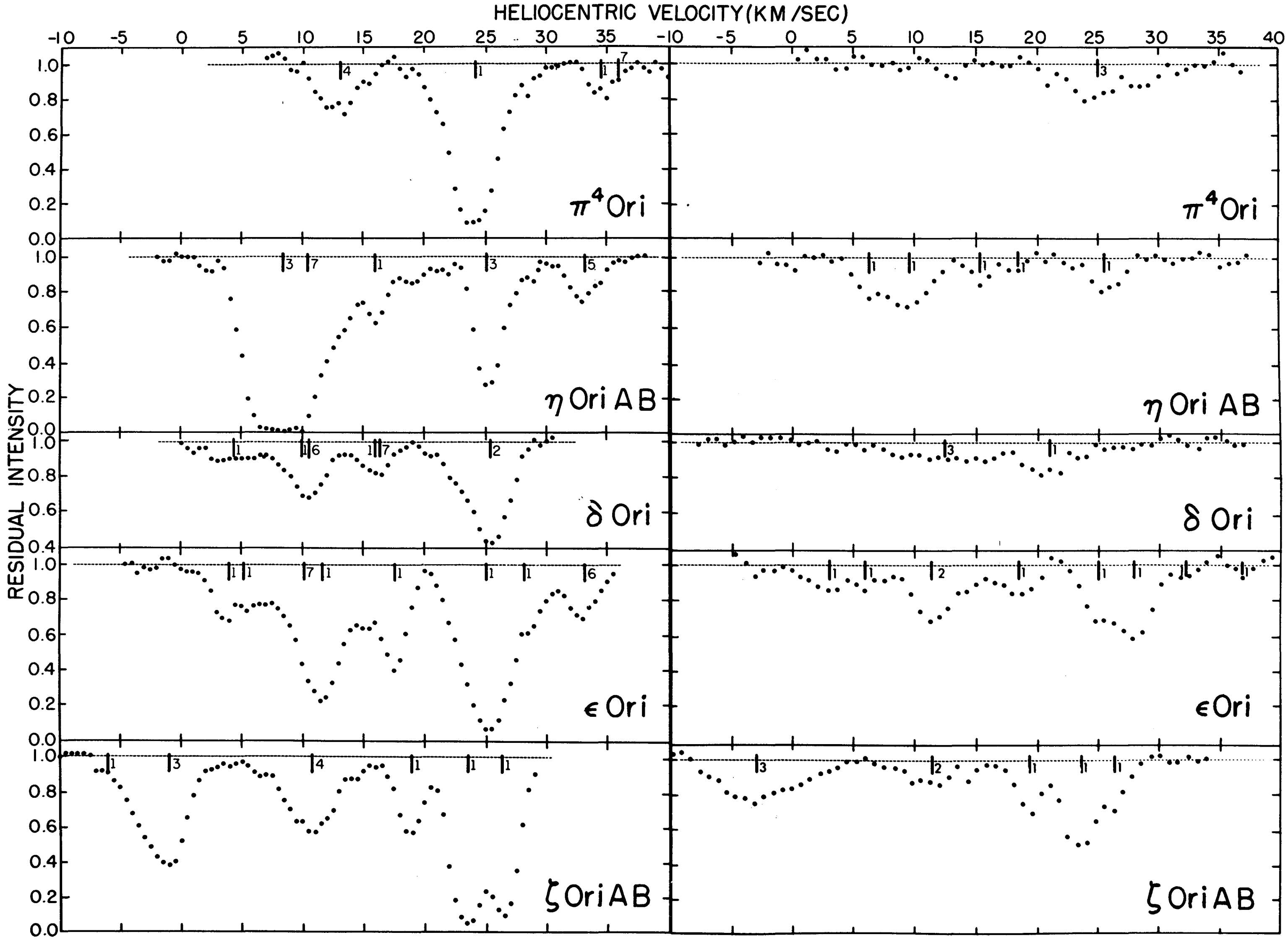

FIG. 2.—The interstellar sodium D_2 and calcium K-lines in the spectra of five Orion stars. The calcium scans appear in the right-hand half of the figure.

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