

THE SPECTRUM OF CHI CYGNI NEAR MINIMUM LIGHT

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ABSTRACT

Long-exposure spectrograms chiefly by I. S. Bowen with the 200-inch telescope show the extraordinary behavior of the rich bright-line spectrum of the long-period variable χ Cygni near minimum light. Of 60 bright lines whose intensities increase markedly during the two months preceding minimum, one-third are forbidden lines of $Fe\ II$, two-thirds are unidentified. Differences in radial velocity between various groups of lines and between plates at various phases are small. A few suggestions for future observations are included.

The variable star χ Cygni, period 406 days, is famous for its great changes in brightness, the mean range in visual magnitude being from 5.3 to 13.3, with reported extremes of 2.3 and 14.3. Its absorption spectrum combines characteristics of classes M and S. At most phases of the light-cycle, numerous bright lines are conspicuous on the spectrograms; their behavior illustrates the general rule concerning long-period variables, that the greater the amplitude of light-variation, the more intense are the bright lines.

TABLE 1
SPECTROGRAMS OF χ CYGNI

PLATE	OBSERVER	DATE	JD 243	VIS. MAG.	PHASE (DAYS)		EXPOSURE (HOURS)	DISP. (A/M μ)
					From Max.	From Min.		
Ce 3505. . . .	P. W. M.	1944 July 10-11	1282	11.4	+162	-76	13.2	10
Pc 67.	I. S. B.	1951 Mar. 22	3728	11.1	+155	-87	3.7	9
Pd 82.	O. C. W.	Apr. 14	3751	12.1	+178	-64	3.7	18
Pd 91.	I. S. B.	May 12	3779	13.1	+206	-36	3.4	18
Pd 93.	I. S. B.	May 15-17	3783	13.1	+210	-32	19.3	18
Pd 113.	I. S. B.	June 23-25	3822	13.0	+249	+7	23.1	18
Pe 356.	I. S. B.	1952 June 30	4194	13.3	+217	-18	7.0	38

Low-dispersion spectrograms obtained with the 100-inch telescope in October, 1935, just before minimum light showed several individual bright lines and, in addition, a few emission patches of bright lines hopelessly blended.¹ Spectrograms with higher dispersion obtained in 1944 during the postmaximum phase disclosed a rich bright-line spectrum, including some conspicuous lines that could not be identified.²

During the spring of 1951, I. S. Bowen and O. C. Wilson obtained with the 200-inch telescope a number of spectrograms near the minimum phase, and in June, 1952, Dr. Bowen obtained an additional plate (see Table 1 and Fig. 1). My best thanks go to these observers for placing their long-exposure photographs at my disposal. The photometric data were kindly supplied by Mrs. Margaret Mayall, of the Harvard Observatory.

¹ P. W. Merrill, *Mt. W. Contr.*, No. 539; *A p. J.*, 83, 272, 1936.

² P. W. Merrill, *Mt. W. Contr.*, No. 735; *A p. J.*, 106, 274, 1947.

Because the medium-dispersion Pd plates were taken before the adjustments of the coudé spectrograph were completed, the definition is imperfect, being decidedly inferior to that attained later. The strongly exposed low-dispersion plate Pe 356 is sharp from λ 3760 to λ 4400.

Data derived from the 100-inch plate Ce 3505 have already been published.² The new spectrograms, besides showing the general behavior nearer minimum light, provide more accurate wave lengths for many of the bright lines in the previous list and yield 24 additional lines, about half of them unidentified.

The chief bright lines measured in the spectrum toward the phase of minimum light are listed in Table 2. The wave lengths are mean values from several plates, including Ce 3505. For each plate the measured wave lengths were corrected for the radial velocity derived from the lines of [Fe II]; if the mean velocity from all bright lines had been used, the resulting wave lengths would have been algebraically higher by about 0.02 Å. For the identified lines, the mean residuals from laboratory wave lengths, regardless of sign,

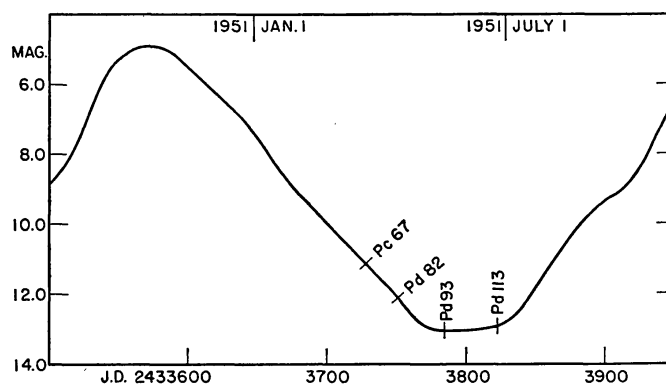


FIG. 1.—Light-curve of α Cygni showing dates of spectrograms in 1951

are 0.05 and 0.04 Å for neutral and ionized lines, respectively. These residuals include, in addition to errors of measurement, displacements intrinsic in the stellar spectrum caused by blending, adjacent absorption lines, etc. For additional lines measured during the postmaximum phase see Table 13 in *Mount Wilson Contributions*, No. 735.²

Cursory descriptions of the behavior of various lines with respect to phase in the light-cycle are given by the symbols in the third column of Table 2 and by a few remarks at the end of the table. A portion of plate Pd 93 is shown in Figure 2. The following notes concern certain interesting changes between plates Pd 93 and Pd 113 taken, respectively, near the beginning and near the end of the flat portion of the light-curve at minimum (Fig. 1):

Lines of [Fe II] and numerous unidentified lines remain of the same intensity or are somewhat strengthened on the later plate. Nearly all lines of Fe I are weakened by a factor of about 2; certain ones more greatly weakened are $\lambda\lambda$ 3852, 3950, 3977, 4206. The displaced emission portions of the Ca II lines λ 3933 and λ 3968 and of the Al I lines λ 3944 and λ 3961 are greatly weakened. Perhaps most notable of all is the marked weakening of the Mn I lines $\lambda\lambda$ 4030, 4033, and 4034, and of the Ga I line λ 4172. This simultaneous weakening tends to confirm my previous suggestion² that the gallium line is fluorescent, the exciting line being one of the manganese lines. A special study of the behavior of these lines in the spectra of several long-period variables has just been published.³

An extremely interesting group of lines in Table 2 comprises those described in the third column by "m!" whose intensities increased markedly during the two months preceding minimum light. Of the 60 lines thus listed, one-third are forbidden lines of Fe II;

³ Paul W. Merrill and Louise Lowen, *Pub. A.S.P.*, 65, 221, 1953.

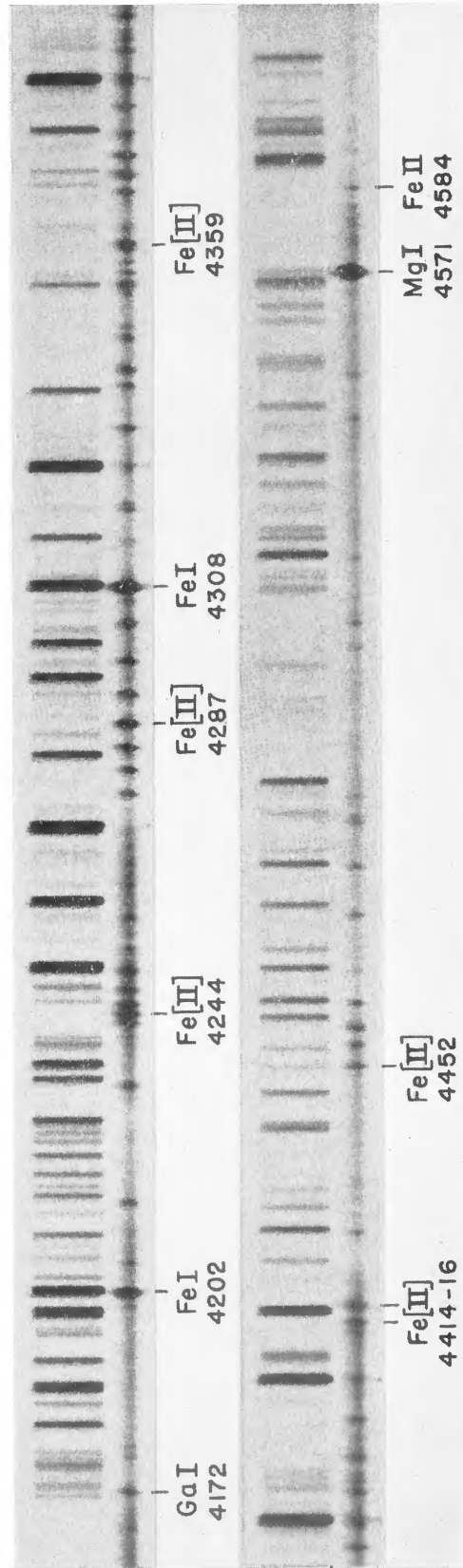


FIG. 2.—The spectrum of α Cygni, 32 days before minimum light. Plate Pd 93, taken by I. S. Bowen, June 23-25, 1951

TABLE 2
BRIGHT LINES IN THE SPECTRUM OF χ CYGNI NEAR MINIMUM LIGHT

I.A.	Max. Int.	Change with Phase*	Ident.	I.A.	Max. Int.	Change with Phase*	Ident.
3277.34	8	p, r1	.35 Fe II (1)	4081.47	4	m!	.....
3521.27	8	p	.26 Fe I (24)	84.46	3	m!	.....
35.18	4	p	.16 Zr I (59)	86.28	1	p	.30 Co I (58)
65.39	16	p	.38 Fe I (24)	87.98	3	m!	.....
3608.86	5	p	.86 Fe I (23)	92.04	3	m!	.....
3735.35	20	m!	.....	93.56	1	m!	.....
49.45	4	p	.49 Fe I (21)	95.52	2	d	.....
57.98	1	p	.24 Fe I (21)	96.83	2	m!	.....
59.26	2	p	.29 Ti II (13)	98.19	2	m!	.....
61.34	2	p	.32 Ti II (13)	4101.74	.....	d	.74 H δ
63.78	3	p	.79 Fe I (21)	03.08	2	p	.93 Si I (2)
67.18	1	p	.19 Fe I (21)	08.84	5	m!	.....
70.5	.....	d	.63 H 11	14.70	2	m!	.48 Fe II (23F)?
87.89	1	p	.88 Fe I (21)	18.80	2	d	.77 Co I (28)
98.0	.....	d	.90 H 10	29.02	1	m!	.....
98.52	2	p	.51 Fe I (21)	66.58	2	d	.51 Zr I (-)
3812.99	1	p	.96 Fe I (22)	72.07	8	d!	.05 Ga I (1)
15.88	1	p	.84 Fe I (45)	77.32	3	m!	.21 Fe II (21F)
20.38	2	p	.43 Fe I (20)	78.84	2	p	.86 Fe II (28)
25.79	2	p	.88 Fe I (20)	4202.06	30	p	.03 Fe I (42)
27.85	2	p	.82 Fe I (45)	06.61	3	p	.70 Fe I (3)
29.36	4	p	.35 Mg I (3)	15.51	6	p	.52 Sr II (1)
32.30	6	p	.30 Mg I (3)	16.05	2	p	.18 Fe I (3)
34.13	1	p	.22 Fe I (20)	25.3	(2)	m, r4	.73 Ca I (2)
35.42	.....	d	.39 H η	33.12	5	p	.17 Fe II (27)
38.28	8	p	.29 Mg I (3)	40.42	2	d	.44 Zr I (-)
41.12	2	p	.05 Fe I (45)	42.52	8	m!	.61 Zr I (-), —
45.51	1	p	.47 Co I (34)	43.80	14	m!, r5	.98 Fe II (21F)
52.63	12	d	.57 Fe I (73)	45.26	8	m!	.....
58.26	1	p	.30 Ni I (32)	47.42	7	m!	.....
87.10	2	p	.05 Fe I (20)	50.30	5	m!	.....
88.99	.....	d	.05 H ζ	50.72	1	d	.79 Fe I (42)
3905.53	8	p	.53 Si I (3)	58.28	3	d	.32 Fe I (3)
32.9	4	r2	.66 Ca II (1)	71.74	1	d	.76 Fe I (42)
35.97	1	p	.96 Co I (32)	76.84	10	m!	.83 Fe II (21F)
38.31	3	p	.29 Fe II (3)	80.48	8	m!	.....
43.8	2	r3	.01 Al I (1)	82.64	2	d	.41 Fe I (71)?
50.01	4	p	.95 Fe I (72)	83.77	10	m!	.....
61.4	2	r3	.52 Al I (1)	87.42	30	m!	.40 Fe II (7F)
67.9	8	r2	.47 Ca II (1)	91.83	11	m!	.....
70.00	.....	d	.07 He	96.70	7	m!	.....
77.81	3	p	.74 Fe I (72)	4300.10	1	d	.05 Ti II (41)
92.99	2	m	.....	02.11	2	d	.93 Ti II (41)
95.34	2	d	.31 Co I (31)	03.0	1	d	.17 Fe II (27)
4020.94	1	d	.90 Co I (16)	05.81	2	m!	.90 Fe II (21F)
30.68	9	d	.76 Mn I (2)	07.90	40	p	.91 Fe I (42)
33.03	5	d	.07 Mn I (2)	15.02	1	d	.98 Ti II (41)
34.43	5	d	.49 Mn I (2)	19.62	6	m!	.62 Fe II (21F)
45.73	2	d	.80 Fe I (43)	20.52	6	m!	.....
63.57	1	d	.60 Fe I (43)	25.8	3	m, r6	.76 Fe I (42), —
66.52	2	m	.....	31.77	10	m!	.....
68.72	4	m	.62 S II (1F)	38.18	6	m!	.....
71.27	2	m!	.....	40.43	.....	d	.47 H γ
73.77	2	m!	.....	45.26	6	m!	.....
77.62	2	p	.71 Sr II (1)	46.84	2	m!	.85 Fe II (21F)
78.93	2	m!	.....	51.80	2	p	.76 Fe II (27)
80.5	1	m!	.....	52.78	2	m!	.78 Fe II (21F)

TABLE 2—Continued

I.A.	Max. Int.	Change with Phase*	Ident.	I.A.	Max. Int.	Change with Phase*	Ident.
4353.26.....	9	m!	.....	4457.94.....	8	m!	.95 Fe II (6F)
54.98.....	5	m!	.....	61.59.....	6	m	.65 Fe I (2)
56.59.....	3	m!	.....	66.59.....	1	m	.57 Fe I (2)
58.44.....	4	m!	.37 Fe II (21F)	74.88.....	5	m!	.91 Fe II (7F)
59.36.....	10	m!	.34 Fe II (7F)	82.13.....	3	m	.17 Fe I (2)
61.81.....	4	m!	.....	88.8.....	2	m!	.75 Fe II (6F)
67.07.....	10	m!	.....	89.7.....	2	m	.74 Fe I (2)
69.59.....	10	m!, r7	.....	4509.6.....	1	m!	.61 Fe II (6F)
72.46.....	15	p	.38 Ti I (277)?	11.32.....	2	d	.31 In I (1)
75.84.....	3	p	.93 Fe I (2)	15.0.....	2	m, r8	.90 Fe II (6F)
79.82.....	4	m!	.....	18.74.....	3	m!	.....
83.42.....	2	p	.54 Fe I (41)	20.16.....	1	d	.22 Fe II (37)
84.40.....	3	m!	.....	22.64.....	1	d	.63 Fe II (38)
88.10.....	3	m!	.....	28.53.....	2	d	.61 Fe I (68)
89.75.....	1	m!	.....	49.46.....	2	d	.47 Fe II (38)
91.0.....	1	m!	.....	55.93.....	1	d	.89 Fe II (37)
93.34.....	8	m!	.....	71.10.....	40	p	.10 Mg I (1)
99.03.....	4	m!	.....	83.77.....	2	p	.83 Fe II (38)
4400.61.....	1	d	.....	4629.31.....	3	m	.34 Fe II (37)
04.8.....	1	d	.75 Fe I (41)	39.9.....	5	m!	.68 Fe II (4F)
05.32.....	2	m!	.....	4728.00.....	3	m!	.07 Fe II (4F)
13.80.....	6	m	.78 Fe II (7F)	4814.54.....	5	m!	.55 Fe II (20F)
16.30.....	5	m!	.27 Fe II (6F)	61.23.....	.....	p	.33 H β
27.26.....	4	p	.31 Fe I (2)	89.59.....	2	m!	.63 Fe II (4F)
52.13.....	8	m!	.11 Fe II (7F)	4923.90.....	2	p	.92 Fe II (42)
55.34.....	8	m	.....	5018.41.....	?	p	.43 Fe II (42)

* The letters in this column have the following meanings: p = persistent throughout much of the time of declining light; d = intensity decreases toward minimum light; m = intensity increases toward minimum light; r = remark.

REMARKS

1. λ 3277.34. Measured in the fourth order on several Palomar plates. Previous observations have shown the bright Fe II lines of multiplet (1) to be surprisingly strong; these lines merit extensive observation in the spectra of χ Cygni and other long-period variables.
2. Displaced Ca II emission; the effective wave length increases toward minimum light.
3. Displaced Al I emission; the effective wave length increases slightly toward minimum light.
4. λ 4225.3. Displaced Ca I emission; grows stronger toward minimum light but is never outstanding.
5. λ 4243.80. On the higher-dispersion plates the line is seen to have components at λ 4243.67 and λ 4243.99. The second line probably corresponds to [Fe II] (21F) λ 4243.98; the other line has not been identified.
6. λ 4325.8. The intensity and wave length increase toward minimum light as if a line of wave length about λ 4326.1 were blending with λ 4325.76 Fe I (42).
7. λ 4369.59. The intensity increases rapidly toward minimum light. On the Palomar plates this line is blended with the fourth-order image of λ 3277.35.
8. λ 4515.0. The intensity increases and the wave length decreases toward minimum light. Probably a blend of λ 4515.34 Fe II (37) and λ 4514.90 Fe II (6F).

the remaining two-thirds are as yet unidentified. A number of the strongest lines have been observed in the spectra of other long-period variables toward minimum light; hence it seems probable that they are characteristic of these variables and that their emission in such great intensity depends, in some way as yet unexplained, on physical processes involved in the large changes in total light.

It is surprising that such a large group of lines, many of them of great intensity compared to the adjacent continuous spectrum, should defy identification. The chief possibilities would appear to be the following:

1. Lines of rare or unstable elements, especially those of high atomic number (e.g.,

rare earths), not yet included in comprehensive spectroscopic lists. This seems improbable; but the appearance of absorption lines of $Tc\ I$ in the spectra of χ Cygni and of other long-period variables also seemed improbable.

2. Weak lines of certain elements, or possibly individual band lines of certain compounds, tremendously intensified by fluorescence. Circumstantial evidence is unfavorable. Many strong lines, including several ascribed to fluorescent effects, are decreasing in intensity at the same time that the unidentified lines are increasing.

3. Forbidden lines not observable in the laboratory. Because the general behavior of the unidentified lines somewhat parallels that of numerous lines of $[Fe\ II]$, this is perhaps

TABLE 3
RADIAL VELOCITIES FROM EMISSION LINES (KM/SEC)

PLATE	PHASE FROM MIN. (DAYS)	H		Fe I		Mg I		Fe II		[Fe II]		χ Cyg*		MEAN VEL.
		Vel.	No.	Vel.	No.	Vel.	No.	Vel.	No.	Vel.	No.	Vel.	No.	
Pc 67.....	-87	-16.0	5	-15.1	29	-15.9	4	-13.9	12	-12.5	15	-14.5	24	-14.4
Ce 3505...	-76	-13.6	7	-15.2	76	-18.2	4	-14.6	18	-13.5	14	.....	.....	-14.9
Pd 82.....	-64	-18.6	5	-14.0	29	-19.5	4	-14.1	16	-11.7	13	-16.8	30	-15.0
Pd 93.....	-32	-15.2	5	-11.2	30	-9.5	4	-11.0	11	-10.3	13	-12.7	33	-11.7
Pe 356.....	-18	-14.2	4	-10.0	18	-10.2	3	-13.6	3	-13.3	5	-10.8	21	-11.1
Pd 113....	+ 7	- 4.9	4	- 7.4	15	- 0.8	4	- 5.3	2	- 8.5	13	- 7.5	30	- 7.1

* Unidentified lines from Table 13, *Mt. W. Contr.*, No. 735; *Ap. J.*, **106**, 274, 1947.

TABLE 4
MEAN VELOCITIES FROM EMISSION LINES (KM/SEC)

Plates	Phase from Min. (Days)	H	Fe I	Mg I	Fe II	[Fe II]	χ Cyg	All
<i>Contr.</i> No. 735.....	-138	-14.4	-16.9	-17.1	-14.6	-14.0	.....	-15.4
Pc 67, Ce 3505, Pd 82.....	- 71	-15.5	-15.0	-17.5	-14.3	-12.7	(-15.4)	-14.7
Pd 93, Pe 356.....	- 27	-14.9	-10.9	- 9.7	-11.6	-11.1	-12.2	-11.6
Pd 113.....	+ 7	- 5	- 7	- 1	- 5	- 8	- 8	- 7.1
All except Pd 113.....	- 79	-15.6	-13.7	-15.2	-13.5	-12.1	-14.2	-13.8
All.....	- 57	-13.9	-12.7	-12.4	-12.7	-11.6	-12.5	-12.6

the best guess. But I have not detected any significant correspondence with the most likely lines computed for abundant elements.⁴

Radial velocities from emission lines.—Data concerning radial velocities derived from various groups of lines are recorded in Table 3. Mean values appear in Table 4. Differences between results from various plates and between those from various elements on the same plate are small. In other long-period variables the bright lines of $Fe\ II$ have a well-marked positive displacement with respect to lines of neutral atoms, but this effect is not noticeable in χ Cygni. As minimum is approached, there appears a slight general tendency of all bright lines toward algebraically higher values. The especially high value from Pd 113, seven days after minimum, needs confirmation because the definition on this plate was not good. Because of the extremely large magnitude range exhibited by χ Cygni, I am

⁴ Charlotte E. Moore, *A Multiplet Table of Astrophysical Interest (Contr. Princeton U. Obs., No. 20, 1945)*.

surprised that the differences in velocity are not larger; but in such matters it is better to ask the stars than to tell them.

Absorption lines.—The absorption lines will be discussed very briefly because they are not shown satisfactorily on the new spectrograms. The great intensity of the $K\ I$ lines $\lambda\ 4044$ and $\lambda\ 4047$ is noteworthy. Because of the low ionization potential of potassium, these lines are extremely sensitive indicators of temperature in the reversing layers of long-period variables. Asymmetrical emission within the broad absorption $Ca\ I$ line $\lambda\ 4227$ is seen on the three or four plates nearest minimum. Similar behavior was previously observed in the spectrum of R Leonis.⁵

The meager data on radial velocities yielded by the absorption lines are summarized in Table 5. The velocities do not differ appreciably from those obtained in other years

TABLE 5
RADIAL VELOCITIES FROM ABSORPTION LINES

Plate	Phase from Min. (Days)	Vel. (Km/Sec)	No.	Plate	Phase from Min. (Days)	Vel. (Km/Sec)	No.
Ce 3505.....	-76	-6	21	Pe 356.....	-18	(0)	5
Pd 93.....	-32	-5	10	Pd 113.....	+ 7	0	14

nearer maximum light.^{2, 6} Hence there is little evidence of change of velocity with phase. If volume pulsations exist in this star, it would seem that the changes in diameter of the reversing layer do not exceed a very few per cent.

Suggestions for future observations.—The present investigation has raised challenging problems concerning the spectra of long-period variables near minimum light. Because certain rapid changes occur, a series of plates of χ Cygni taken at intervals of two weeks right through the minimum phase would be desirable. Even with the fairly low dispersion of 38 A/mm, an all-night exposure with a very large telescope would be required; with 18 A/mm three nights would be needed for a strong exposure. After 1953, conjunction with the sun will interfere with observations near minimum for seven or eight years. Other variables that might be considered for intensive spectroscopic observation near minimum are R Leo, R Hya, R Cas, T Cep, as well as the S-type stars R And and R Cyg.

A few exploratory observations in the spectral region between $H\beta$ and $H\alpha$ might be in order. Here the band absorption is very strong, but, since the effective level of emission seems to rise as the phase advances, perhaps toward minimum some bright lines (coronal or other forbidden lines?) might put in an appearance and yield hints that would help to dispel the deep mystery that now surrounds these variables.

⁵ P. W. Merrill, *Mt. W. and P. Repr.*, No. 72; *Ap. J.*, 116, 337, 1952.

⁶ P. W. Merrill, *Mt. W. Contr.*, No. 649; *Ap. J.*, 94, 171, 1941.