NBS

Technical Note No. 214

ABSOLUTE PHOTOMETRY OF THE LIGHT OF THE NIGHT SKY

The Zenith Intensity of Haleakala (latitude N 20.7°) and at Fritz Peak (latitude N 39.9°)

F. E. ROACH AND L. L. SMITH

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards is a principal focal point in the Federal Government for assuring maximum application of the physical and engineering sciences to the advancement of technology in industry and commerce. Its responsibilities include development and maintenance of the national standards of measurement, and the provisions of means for making measurements consistent with those standards; determination of physical constants and properties of materials; development of methods for testing materials, mechanisms, and structures, and making such tests as may be necessary, particularly for government agencies; cooperation in the establishment of standard practices for incorporation in codes and specifications; advisory service to government agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; assistance to industry, business, and consumers in the development and acceptance of commercial standards and simplified trade practice recommendations; administration of programs in cooperation with United States business groups and standards organizations for the development of international standards of practice; and maintenance of a clearinghouse for the collection and dissemination of scientific, technical, and engineering information. The scope of the Bureau's activities is suggested in the following listing of its four Institutes and their organizational units.

Institute for Basic Standards. Electricity. Metrology. Heat. Radiation Physics. Mechanics. Applied Mathematics. Atomic Physics. Physical Chemistry. Laboratory Astrophysics.* Radio Standards Laboratory: Radio Standards Physics; Radio Standards Engineering.** Office of Standard Reference Data.

Institute for Materials Research. Analytical Chemistry. Polymers. Metallurgy. Inorganic Materials. Reactor Radiations. Cryogenics.** Office of Standard Reference Materials.

Central Radio Propagation Laboratory.** Ionosphere Research and Propagation. Troposphere and Space Telecommunications. Radio Systems. Upper Atmosphere and Space Physics.

Institute for Applied Technology. Textiles and Apparel Technology Center. Building Research. Industrial Equipment. Information Technology. Performance Test Development. Instrumentation. Transport Systems. Office of Technical Services. Office of Weights and Measures. Office of Engineering Standards. Office of Industrial Services.

---

* NBS Group, Joint Institute for Laboratory Astrophysics at the University of Colorado.

** Located at Boulder, Colorado.

NATIONAL BUREAU OF STANDARDS
Technical Note 214
Issued June 29, 1964

ABSOLUTE PHOTOMETRY OF THE LIGHT OF THE NIGHT SKY

The Zenith Intensity of Haleakala (latitude N 20.7°) and at Fritz Peak (latitude N 39.9°)

F. E. Roach and L. L. Smith
Central Radio Propagation Laboratory
National Bureau of Standards
Boulder, Colorado

NBS Technical Notes are designed to supplement the Bureau's regular publications program. They provide a means for making available scientific data that are of transient or limited interest. Technical Notes may be listed or referred to in the open literature.

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington, D.C. 20402
Price: 35 cents

CONTENTS

PAGE

ABSOLUTE PHOTOMETRY OF THE LIGHT OF THE NIGHT SKY

The Zenith Intensity at Haleakala (latitude N 20.7°) and at Fritz Peak (latitude N 39.9°)

F. E. Roach and L. L. Smith*

Central Radio Propagation Laboratory
National Bureau of Standards, Boulder, Colorado

and

Institute of Geophysics
University of Hawaii, Honolulu, Hawaii

A study is presented of one year of systematic zenith observations made with similar photometers at two observing stations: Haleakala (latitude N 20.7°) and Fritz Peak (latitude N 39.9°). It is shown that, for an effective wavelength of 5300 A, there is a change of intensity with sidereal time (and therefore right ascension) due to three components: (1) integrated starlight, (2) zodiacal light, and (3) airglow continuum. Quantitative separation of the components is made. A critical comparison is made with some earlier investigations with particular reference to the problem of the galactic light.

---

*This paper was prepared while the authors were guests at the Institute of Geophysics of the University of Hawaii. F. E. Roach was the recipient of a Senior Specialist Award from the East-West Center of the University of Hawaii for the academic year 1963-64.

1. INTRODUCTION

The light of the night sky includes three primary sources: (1) An astronomical component due to the light from stars and nebulae, (2) a solar system component (zodiacal light) due to sunlight scattered chiefly by dust in interplanetary regions, and (3) a terrestrial component (airglow) originating in the Earth's upper atmosphere.

If a filter is employed which excludes strong airglow emissions, the airglow component cannot be identified with a specific resolved emission, and it has become customary to refer to it as a "continuum" even though the possibility exists that it may actually be the summation of many discrete emission features, each of which is too faint to be recorded even on long-exposure spectrograms.

The earth-bound observer not only has to attempt the resolution of the three components but also must contend with the effects of the extinction and scattering of the lower atmosphere. The problem of making the extinction and scattering corrections becomes progressively more difficult as the horizon is approached but, fortunately, zenith observations are not seriously affected.

A random zenith observation includes the starlight, zodiacal light and airglow components in unknown proportions. To effect an initial separation, we have taken advantage of the fact that, in the first approximation, the starlight and zodiacal light vary with sidereal time, whereas the airglow does not. The separation of the starlight and zodiacal light is accomplished in a series of approximations utilizing the systematic changes of galactic and ecliptic coordinates of the zenith (Figure 1 and Table 1) as a function of sidereal time.

2. THE OBSERVATIONAL MATERIAL

The observations utilized are a portion of the material obtained at the two stations with standardized zenith photometers as described by Purdy, Megill and Roach [1961]. The full program includes records of

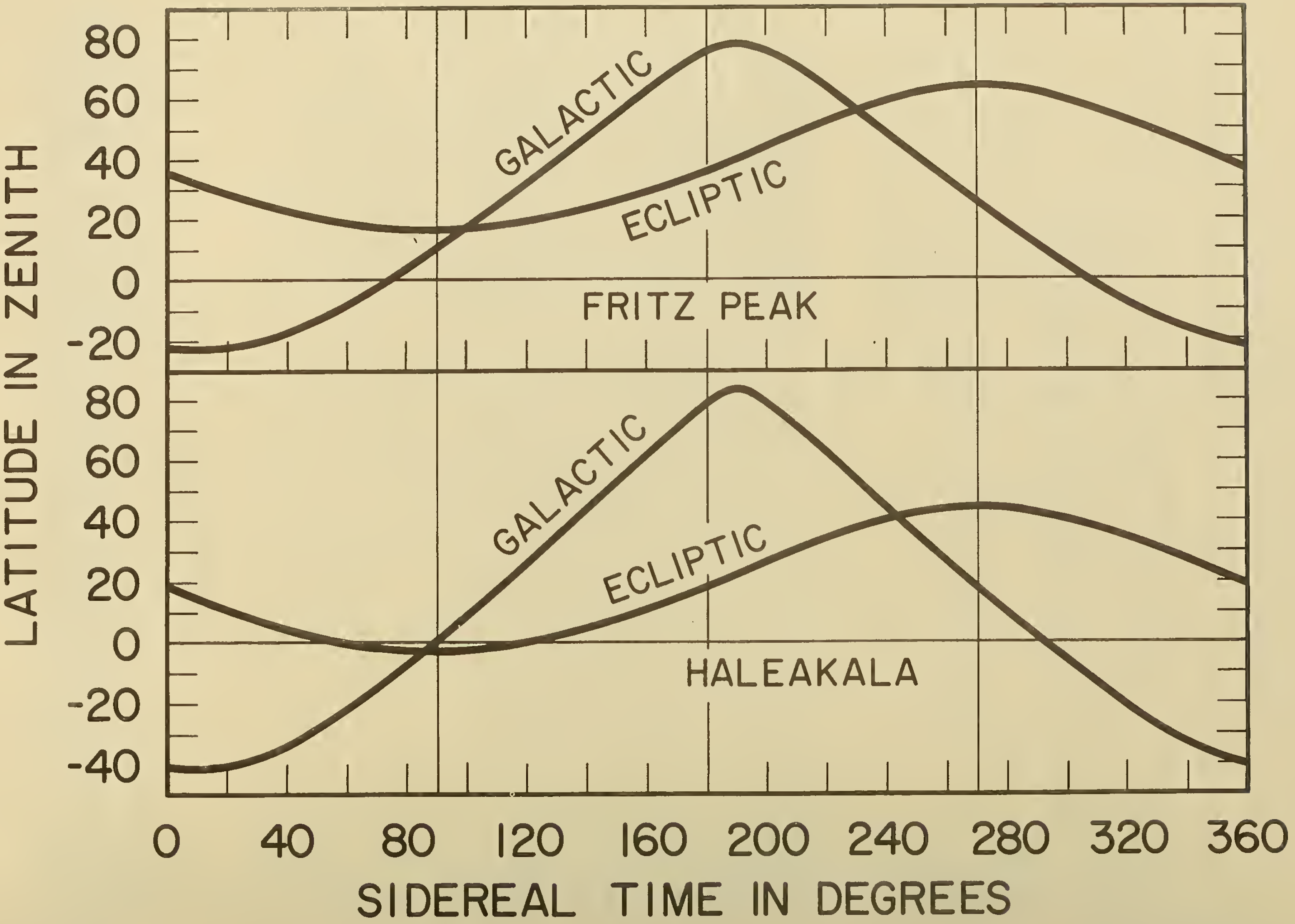

Figure 1. Ecliptic and galactic latitude of the zenith for Fritz Peak and Haleakala as a function of the sidereal time.

TABLE 1

Galactic and Ecliptic Coordinates for the Zenith

	HALEAKALA				FRITZ PEAK			
Sidereal Time	Galactic		Ecliptic		Galactic		Ecliptic	
	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
10°	-42°	89°	15°	18°	-22°	91°	32°	27°
20	-41	102	11	26	-22	98	29	35
30	-38	113	8	35	-20	106	26	42
40	-34	124	5	44	-17	113	23	50
50	-28	133	2	53	-13	120	21	58
60	-22	140	0	62	- 8	126	19	66
70	-15	146	- 1	71	- 3	131	18	74
80	- 7	152	- 3	81	3	136	17	83
90	1	157	- 3	90	10	140	17	90
100	9	161	- 2	99	17	143	17	98
110	17	165	- 2	109	24	146	18	106
120	26	169	0	118	32	148	19	114
130	35	173	2	127	39	149	21	122
140	44	177	5	136	47	150	23	130
150	52	182	8	145	54	149	26	138
160	61	187	11	154	62	146	29	145
170	70	196	15	163	69	139	32	153
180	78	214	19	171	75	123	36	162
190	83	265	23	180	78	88	40	170
200	79	323	27	190	75	60	44	179
210	71	342	31	200	70	43	48	188
220	62	352	34	210	63	35	52	199
230	54	358	38	221	55	31	55	210
240	45	2	40	232	48	30	59	223
250	36	6	42	244	40	30	61	237
260	27	10	44	257	33	32	63	253
270	19	14	44	270	25	34	63	270
280	10	18	44	283	18	36	63	287
290	2	23	42	296	11	40	61	303
300	- 6	27	40	308	4	44	59	317
310	-14	33	38	319	- 2	48	55	330
320	-21	39	34	330	- 8	53	52	341
330	-28	47	31	340	-12	59	48	352
340	-33	55	27	350	-17	66	44	1
350	-38	65	23	359	-20	73	40	10
360°	-41°	77°	19°	8°	-22°	81°	36°	18°

zenith intensities using interference filters centered on 5300 A, 5577 A, 5893 A, and 6300 A, the last three for specific airglow emissions and the first as a general control for the estimation of background radiations and their elimination from the emission filter data. The present study is concerned with the 5300 A observations only.

The totality of data includes 153 nights of observations at Haleakala (from July 12, 1961, to July 25, 1962) and 108 nights at Fritz Peak (from December 31, 1961, to January 1, 1963). Zenith intensities relative to a built-in standard light are recorded at 5-minute intervals corresponding to changes of 1-1/4° in sidereal time. Considerable overlap thus occurs, each sidereal time having many independent observations*, making it possible to average out sporadic changes.

The principal results of this study are given in Tables 2 and 3: in Table 2 the total light and the integrated starlight for each degree of sidereal time and in Table 3 the mean zodiacal light intensities as a function of ecliptic latitude.** The resolution of the three components was accomplished in a series of approximations which will be outlined in the next section. In Table 4 we summarize the over-all averages of the components for the two stations. All intensities are given in units of S_{10} (visual) units (see Appendix A) referred to "outside the atmosphere."

3. THE SEPARATION OF STARLIGHT, ZODIACAL LIGHT AND AIRGLOW

In Figure 2 we show the grand-average curves of the observed intensities for the two stations as a function of sidereal time. A casual inspection of Figure 2 shows immediately the intensification of the two arms of the Milky Way as they traverse the zenith near sidereal times 80° and 300°. A more than casual inspection brings out what was known decades ago by the classical astronomers, namely that the contrast between the Milky Way and the sky in the vicinity of the galactic pole

---

*Each degree of sidereal time included between 15 and 30 individual readings.

**Since a given sidereal time corresponds to a given zenith value of the ecliptic latitude (Table 1) the zodiacal light component assumed by us for a given sidereal time (Table 2) may be found by reference to Table 3.

Table 2

OBSERVED TOTAL INTENSITY (OMITTING BRIGHT STARS) AND DEDUCED INTEGRATED STARLIGHT IN THE ZENITH OF HALEAKALA AND FRITZ PEAK AS A FUNCTION OF SIDEREAL TIME

Intensities In S_{10} (vis) Units

	HALEAKALA		FRITZ PEAK			HALEAKALA		FRITZ PEAK	
Sidereal Time	Total	Integrated Starlight	Total	Integrated Starlight	Sidereal Time	Total	Integrated Starlight	Total	Integrated Starlight
1°	263	68	298	111	46°	306	84	364	152
2	263	68	299	110	47	308	86	366	154
3	264	69	300	111	48	308	86	368	154
4	265	68	301	112	49	310	86	370	156
5	265	68	302	112	50	310	86	371	157
6	265	66	303	113	51	311	87	373	159
7	266	67	304	114	52	311	87	375	159
8	266	67	305	113	53	312	88	377	161
9	267	67	306	114	54	312	86	381	165
10	267	67	307	113	55	313	87	403	187
11	268	68	309	115	56	313	87	385	169
12	268	68	310	116	57	313	87	384	168
13	269	67	311	115	58	314	88	392	174
14	270	68	312	116	59	315	87	390	172
15	271	67	313	117	60	316	88	393	175
16	272	68	314	116	61	317	89	359	141
17	272	68	316	118	62	319	91	353	135
18	273	67	317	119	63	321	95	360	142
19	274	68	318	118	64	322	96	358	138
20	275	67	319	119	65	324	98	366	146
21	277	69	320	120	66	326	100	367	147
22	279	71	322	120	67	327	101	373	153
23	281	71	323	121	68	329	103	391	171
24	282	72	325	123	69	331	105	390	170
25	282	72	326	122	70	335	109	397	177
26	284	73	327	123	71	337	113	417	197
27	284	73	328	124	72	341	117	435	213
28	285	74	330	126	73	345	121	454	232
29	286	73	331	126	74	348	124	470	248
30	286	73	333	128	75	352	128	469	247
31	287	74	335	130	76	354	130	473	251
32	288	73	337	130	77	359	135	447	225
33	289	74	339	132	78	365	141	438	216
34	290	75	341	134	79	381	159	433	211
35	291	74	342	135	80	402	180	428	206
36	293	76	344	135	81	406	184	415	193
37	294	77	347	138	82	411	189	407	185
38	296	77	350	141	83	414	192	420	198
39	298	79	352	141	84	419	197	418	196
40	299	80	354	143	85	420	198	416	194
41	300	81	356	145	86	421	199	411	189
42	301	81	357	146	87	422	200	418	196
43	303	83	359	147	88	423	201	422	200
44	304	84	361	149	89	424	202	394	172
45	305	85	362	150	90	438	216	376	154

Table 2

CONTINUE(2)

	HALEAKALA		FRITZ PEAK				HALEAKALA		FRITZ PEAK	
Sidereal Time	Total	Integrated Starlight	Total	Integrated Starlight		Sidereal Time	Total	Integrated Starlight	Total	Integrated Starlight
91°	442	220	369	147		136°	269	49	260	48
92	440	218	365	143		137	268	48	259	47
93	438	216	361	139		138	267	47	257	46
94	434	212	359	137		139	266	47	256	45
95	430	208	356	134		140	265	46	255	44
96	426	204	353	131		141	263	44	253	42
97	423	201	351	129		142	263	44	252	43
98	416	192	348	126		143	262	45	250	41
99	412	188	346	124		144	261	44	249	40
100	408	184	343	121		145	259	42	247	40
101	405	181	340	118		146	258	43	246	39
102	401	177	337	115		147	259	44	245	38
103	396	172	335	113		148	256	41	244	37
104	392	168	332	110		149	254	41	243	38
105	388	164	330	108		150	252	39	242	37
106	378	154	327	105		151	251	38	241	36
107	373	149	324	102		152	249	38	240	36
108	367	143	320	98		153	247	36	240	36
109	360	136	318	98		154	246	35	239	35
110	355	131	315	95		155	244	34	238	34
111	347	121	311	91		156	242	32	238	36
112	338	112	308	88		157	242	32	238	36
113	331	105	304	84		158	241	33	237	35
114	328	102	300	80		159	240	32	237	37
115	325	99	296	76		160	239	31	236	36
116	321	95	293	73		161	239	33	235	35
117	317	89	290	72		162	238	32	235	37
118	314	86	289	71		163	237	31	234	36
119	308	80	287	69		164	236	32	233	35
120	306	78	284	66		165	236	32	232	36
121	301	73	282	64		166	235	33	231	35
122	298	70	280	62		167	234	32	230	34
123	296	70	279	63		168	234	32	230	36
124	294	68	278	62		169	234	34	229	35
125	291	65	276	60		170	233	33	228	34
126	288	62	274	58		171	232	32	227	33
127	286	60	273	57		172	232	33	226	34
128	283	59	271	55		173	231	32	225	35
129	280	56	270	56		174	230	33	225	35
130	278	54	269	55		175	229	32	224	34
131	276	52	267	53		176	228	31	222	33
132	273	51	266	52		177	227	32	222	33
133	272	50	265	53		178	226	31	221	34
134	271	49	263	51		179	225	30	221	34
135	270	48	262	50		180	225	32	220	33

Table 2

CONTINUE (3)

	HALEAKALA		FRITZ PEAK			HALEAKALA		FRITZ PEAK	
Sidereal Time	Total	Integrated Starlight	Total	Integrated Starlight	Sidereal Time	Total	Integrated Starlight	Total	Integrated Starlight
181°	224	31	219	32	226°	217	55	202	47
182	223	32	218	33	227	217	57	202	47
183	223	32	218	33	228	217	57	203	50
184	222	31	217	33	229	217	57	203	50
185	222	33	216	32	230	218	59	204	51
186	222	33	216	32	231	218	59	204	52
187	221	34	215	33	232	219	60	204	52
188	220	33	214	32	233	220	61	205	54
189	220	34	214	34	234	221	64	205	55
190	220	34	213	33	235	222	65	206	56
191	219	33	212	32	236	223	66	206	56
192	218	34	211	33	237	224	67	207	59
193	218	34	211	33	238	226	71	207	59
194	218	34	210	34	239	227	72	208	60
195	217	35	209	33	240	228	73	208	62
196	217	35	208	32	241	229	76	209	63
197	217	37	208	34	242	230	77	209	63
198	216	36	207	33	243	231	78	210	64
199	216	36	206	33	244	232	79	211	67
200	216	37	206	33	245	232	79	211	67
201	216	37	205	32	246	233	82	212	68
202	216	39	204	33	247	234	83	212	68
203	216	39	203	32	248	234	83	213	71
204	217	40	202	32	249	235	84	214	72
205	217	42	201	31	250	236	85	214	72
206	217	42	201	31	251	238	89	214	72
207	217	44	200	32	252	239	90	215	75
208	216	43	199	31	253	240	91	216	76
209	217	44	199	33	254	242	93	216	76
210	217	46	198	32	255	244	95	217	77
211	218	47	198	32	256	246	97	218	78
212	218	47	198	34	257	248	99	218	78
213	218	49	198	34	258	253	105	219	81
214	218	49	199	35	259	256	108	220	82
215	218	49	199	37	260	260	112	221	83
216	218	51	200	38	261	265	117	222	84
217	218	51	200	40	262	269	121	223	85
218	218	53	200	40	263	276	128	230	92
219	218	53	200	40	264	283	135	232	94
220	218	53	200	41	265	289	141	236	98
221	217	53	201	42	266	296	148	242	114
222	217	53	201	44	267	301	153	246	108
223	217	53	201	44	268	307	159	250	112
224	217	55	202	45	269	322	174	254	116
225	217	55	202	47	270	330	182	259	121

Table 2

CONTINUE (4)

	HALEAKALA		FRITZ PEAK				HALEAKALA		FRITZ PEAK	
Sidereal Time	Total	Integrated Starlight	Total	Integrated Starlight		Sidereal Time	Total	Integrated Starlight	Total	Integrated Starlight
271°	334	186	262	124		316°	296	134	438	281
272	338	190	269	131		317	295	131	448	291
273	340	192	275	137		318	294	130	428	261
274	340	192	280	142		319	292	128	416	257
275	344	196	284	146		320	290	125	400	241
276	351	203	288	150		321	288	123	386	226
277	365	217	292	154		322	287	122	383	223
278	379	231	298	160		323	285	118	371	211
279	394	246	302	164		324	283	116	369	207
280	398	250	306	168		325	282	115	347	185
281	389	241	312	174		326	280	111	340	176
282	398	250	316	178		327	279	110	330	166
283	391	242	319	179		328	277	106	322	158
284	392	243	340	200		329	276	105	323	157
285	377	228	360	220		330	274	103	319	153
286	374	225	355	215		331	273	100	318	152
287	375	226	373	233		332	272	99	315	147
288	384	235	374	234		333	270	97	313	145
289	387	238	388	246		334	268	93	311	141
290	391	240	381	239		335	267	92	309	139
291	405	254	386	244		336	266	89	306	136
292	425	284	401	259		337	264	87	304	133
293	461	310	422	278		338	263	86	302	131
294	515	364	451	307		339	262	83	300	127
295	539	386	471	317		340	262	83	298	125
296	545	392	485	341		341	261	81	297	124
297	531	378	491	345		342	260	80	295	121
298	498	345	486	340		343	260	80	293	119
299	477	324	487	341		344	260	78	291	115
300	457	302	495	349		345	259	77	290	114
301	440	285	525	377		346	259	75	288	112
302	428	273	530	382		347	258	74	287	109
303	416	259	520	372		348	258	74	285	107
304	411	264	499	349		349	257	71	283	103
305	404	247	476	326		350	257	71	282	102
306	396	239	451	301		351	256	69	280	100
307	380	221	394	243		352	255	68	278	96
308	354	195	370	219		353	255	68	278	96
309	340	181	366	215		354	255	66	278	94
310	327	168	372	219		355	255	66	280	96
311	320	160	381	228		356	255	66	282	98
312	315	155	397	244		357	256	65	284	99
313	307	147	407	254		358	256	65	286	101
314	300	138	421	266		359	257	64	290	105
315	298	136	444	289		360	259	66	296	109

TABLE 3

Mean Zodiacal Light Intensities
Used in Present Study
S_{10} (vis) Units

Ecliptic Latitude	Zodiacal Light	Ecliptic Latitude	Zodiacal Light	Ecliptic Latitude	Zodiacal Light
0°	185				
1	183	26°	137	51°	92
2	181	27	136	52	91
3	179	28	134	53	89
4	177	29	132	54	87
5	176	30	130	55	85
6	174	31	128	56	83
7	172	32	126	57	82
8	170	33	124	58	80
9	168	34	122	59	78
10	167	35	121	60	76
11	165	36	119	61	74
12	163	37	117	62	72
13	161	38	116	63	70
14	159	39	114	64	69
15	157	40	112		
16	156	41	110		
17	154	42	108		
18	152	43	106		
19	150	44	105		
20	148	45	103		
21	146	46	102		
22	144	47	100		
23	143	48	98		
24	141	49	96		
25	139	50	94		

Table 4.

Summary of Grand Averages
in S_{10} (vis) units.

Contributor	Haleakala	Fritz Peak
Total light (including bright stars)	316	318
Starlight (including bright stars)	126	134
Starlight (excluding bright stars)	103	116
Zodiacal Light	147	116
Airglow	43	68
Sum (excluding bright stars)	293	300

is much less than it would be if starlight were the exclusive source of the light of the night sky. This is sufficiently important to justify a little expansion.

The ratio of intensity in the Milky Way to that at the galactic pole, according to Roach and Megill [1961], is 372/31 = 12. In contrast, Figure 2 illustrates that the observed ratio in our two cases is about 2. The conclusion is inescapable that there must be a very significant source of light in addition to starlight which dilutes the observed ratio compared to its value for starlight alone. The argument is almost trivial, but it illustrates in principle our analytical procedure. About 11/12 (approximately 200 S_{10} (vis) units) of the intensity of the light near the galactic pole is predicted as due to non-stellar sources which is in rough agreement with a more sophisticated interpretation to be presented below.

A similar conclusion is reached by an even more general argument. According to Seares, et al. [1925], the total light from all the stars is equivalent to that from 1092 stars of the first visual magnitude. The mean light per square degree is thus

$$\frac{1092}{41,253} = 0.0265 \text{ first magnitude (visual) stars per square degree}$$

or

$$0.0265 \times 3980 = 105 \text{ 10th magnitude (visual) stars per square degree}^*.$$

We note that the average total zenith intensity at both stations is about 300 S_{10} (vis) (Table 4). Thus again some 200 S_{10} (vis) must be due to the combined zodiacal light and airglow.

We proceed in our discrimination of the components in the following steps: (1) determine the average observed intensity as a function of sidereal time, (2) for each degree of sidereal time, subtract from

---

*For convenience we use the "number of tenth magnitude (visual) stars per square degree" as our unit of intensity and designate it as S_{10} (vis). See Appendix A for a discussion of units.

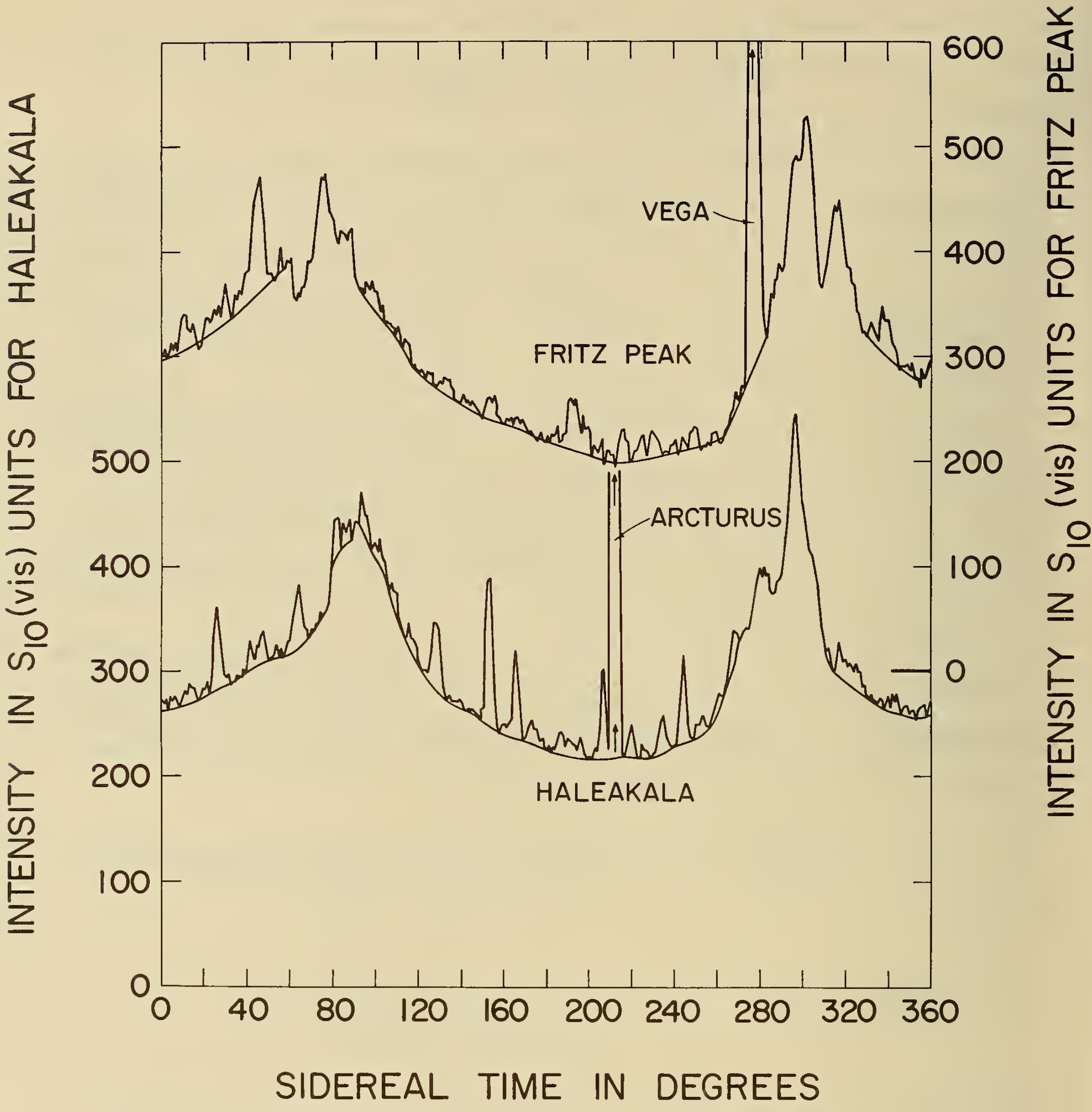

Figure 2. Observed zenith intensities at Fritz Peak and Haleakala as a function of sidereal time. The smooth curves underdrawing the individual star deflections correspond to the "total" entries in Table 2.

the average intensities the corresponding starlight given by Roach and Megill [1961]—the resultant being zodiacal light plus airglow, (3) plot zodiacal light plus airglow versus corresponding zodiacal light results of Roach and Rees [1956]—intercept becomes average airglow, (4) determine zodiacal light, i.e., zodiacal light plus airglow (Step 2) minus average airglow (Step 3), for each degree of sidereal time, (5) deduce starlight, i.e., average observed intensity minus zodiacal light (Step 4) minus average airglow (Step 3), for each degree of sidereal time. This process is repeated as an iteration until further refinements seem to make trivial contributions. We will spare the reader the details of the iteration and proceed to discuss the final results.

4. THE INTEGRATED STARLIGHT

In Figure 2 the deflections due to individual bright stars appear as well-defined spikes. The apparent widths exceed the photometer's field of view (5°) due to the averaging of several observations for each degree of sidereal time with the attendant spread due to inaccuracies in same for observations extending over a long period of time. The fact that our observations were made with 5-minute (1-1/4°) intervals also contributed to a spread in results referred to intervals of 1° in sidereal time. The faintest star that would be detectable as an individual star lies between visual magnitude 5.0 (corresponding to 5 S_{10} (vis) units*) and 6.0 (corresponding to 2 S_{10} (vis) units). For our analysis, we have attempted to underdraw the individual star deflections (the entries labelled "total" in Table 2) in order to permit a comparison with predicted intensities based on star counts. In Figure 3, we show plots of the results of our analysis for integrated starlight, zodiacal light, and airglow as a function of sidereal time for the two stations. As anticipated, the ratio between the intensities in the

---

*The field of view of our photometer is about 20 square degrees. 5 S_{10} (vis) units thus corresponds to 5 x 20 = 100 tenth magnitude stars or 1 fifth magnitude star.

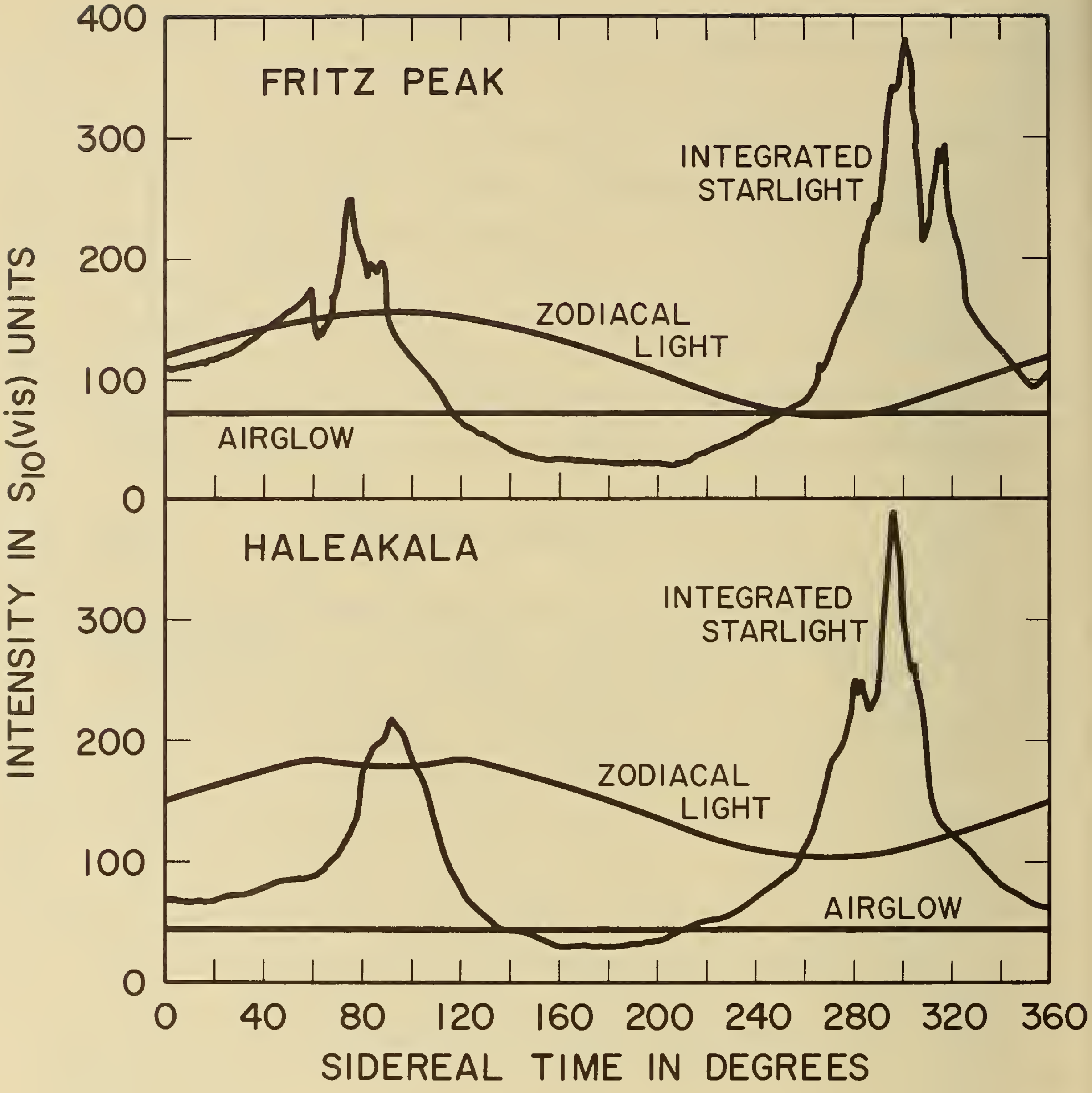

Figure 3. The resolution as a function of sidereal time of the total zenith intensities at Fritz Peak and Haleakala into the three components: airglow, zodiacal light and integrated starlight.

Milky Way and near the galactic pole is now about 10, in substantial agreement with our earlier remarks.

An integration of intensities based on star counts is possible by reference to the classical study of van Rhijn [1925] who published tables of log N_m to m(pg) = 18.0 for 10,296 discrete regions of the celestial sphere.* The results are necessarily highly smoothed since their basis is the 206 "Selected Areas" the study of which was initiated by Kapteyn in 1906. Two isophotal maps of the Milky Way based on the van Rhijn (Groningen publication 43 [referred to hereafter as GR 43]) tables have been published. Roach and Pettit [1951] published a map based on an approximate integration (this map was also included in a paper by Roach, Pettit, Tandberg-Hanssen, and Davis [1954]). More recently, with the help of an electronic computer, Roach and Megill [1961] repeated the integration and published a revised Milky Way map. The difference between the two integrations is not large.

A comparison between our present measurements and the integrations based on star counts is shown in Figure 4. Least-squares solutions give the following relationships between the integrated starlight from the GR 43 integration (G) and our measurements of total intensities, S_t

$$S_t = 201 + 1.18\ G \text{ (Haleakala)} \quad \text{(corr. coeff., } r, = 0.89) \tag{1}$$

$$S_t = 197 + 1.04\ G \text{ (Fritz Peak)} \quad (r = 0.73) \tag{2}$$

It is noted that the intercepts which correspond to the non-stellar contribution are close to 200 S_{10} (vis), as deduced earlier on the basis of general arguments.

The lower curves in Figure 4 show plots of the integrated starlight, S, which we have deduced against the predicted values from the

---

*Log N_m is the logarithm (base 10) of the number of stars per square degree brighter than magnitude m.

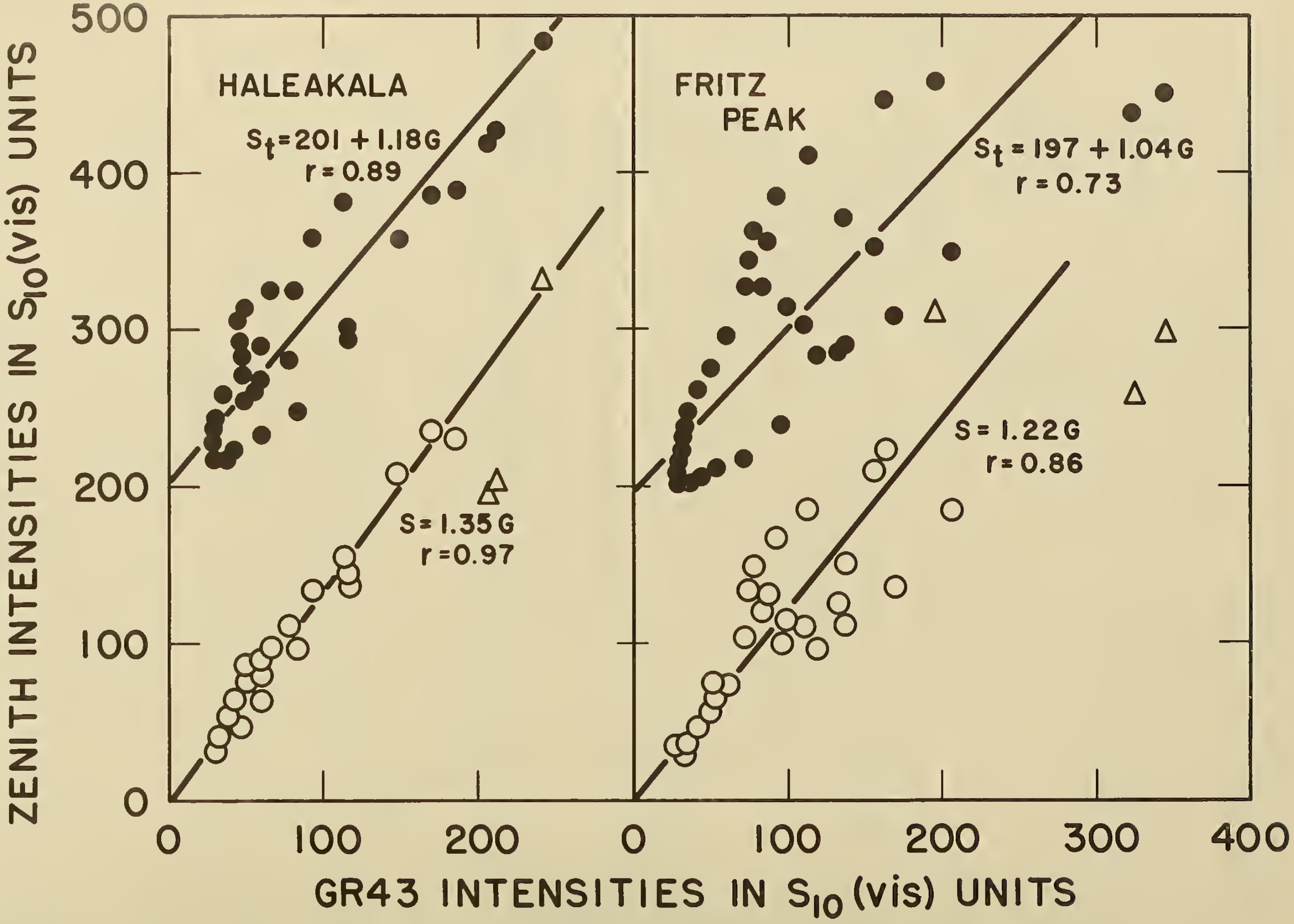

Figure 4. Above: The total zenith intensities as observed at Fritz Peak and Haleakala plotted against the computed integrated starlight based on the star count tables of van Rhijn [1925]. Below: The integrated starlight from the present study plotted against the computed integrated starlight from van Rhijn. Note that each plotted point corresponds to the mean of ten points in Table 2. The points represented by triangles were omitted in the least-squares solutions in the lower plots.

GR 43 integrations. We made successive approximations by adjusting the absolute level of the zodiacal light plus airglow until the deduced integrated starlight plotted against the GR 43 integrated starlight from star counts produced curves which went through the origin. A second requirement was that the two systems should be in agreement at high galactic latitudes. The quality of the final result may be judged by examination of the lower curves in Figure 4. It is to be noted that the scatter of the observational points with respect to straight-line least-squares solutions is much reduced in going from the upper curves which include zodiacal light and airglow to the lower curves in which the zodiacal light and airglow have been subtracted out. Since we have assumed the airglow to be a constant (with respect to sidereal time) the improvement is due to the refinement resulting from subtracting the variable zodiacal light according to the entries of Table 3. It is also noted that the scatter of the points increases for the brighter regions (near the galactic plane) probably due to the severe smoothing that must have entered into the GR 43 tabulations. The least-squares solutions given below omit some of the more discordant points in the Milky Way (see legend for Figure 4)*:

Haleakala
$$S = 1.35\ G \quad (r = 0.97) \tag{3}$$

Fritz Peak
$$S = 1.22\ G \quad (r = 0.86) \tag{4}$$

Haleakala plus Fritz Peak
$$S = 1.26\ G \quad (r = 0.91) \tag{5}$$

---

*A criticism of our procedure is that we have used our judgment in selecting solutions which go through the origin and through the points corresponding to the fainter intensities by omitting some of the discordant high intensity points from the analysis.

5. DISCUSSION OF THE OBSERVATIONAL RESULTS

We now propose to compare our observational results with those obtained by others working in the general domain of the absolute brightness of the light of the night sky with particular reference to the integrated starlight and the zodiacal light.

The intensity of integrated starlight may be considered constant so that similar photometers should give identical absolute intensities for the starlight component for the same region of the sky. There exist, however, serious discrepancies among three observers. These will be discussed in some detail later.

Whether the zodiacal light can be considered constant with time is not so clear. Fluctuations over a few minutes as well as seasonal variations have been reported by several observers, but we are inclined to agree with the general conclusion reached by Barbier [1955] that the reality of such fluctuations and variations is subject to doubt. We propose to make a definitive comparison of four independent measurements of the brightness of the zodiacal light in the ecliptic as a function of the elongation from the sun, ϵ, not only because of its intrinsic interest but also because the comparison helps to explain the divergence of the measured integrated starlight results.

There are two interdependent sources of error encountered in the interpretation of observations of the light of the night sky. First, the three principal components are each of significant brightness and an error in the estimation of any one affects the others. We may call this the subtraction error. Second, the absolute calibration of the photometer is critical since an error in calibration affects a particular component both directly by a multiplication error and indirectly by the possibility of contributing to a subtraction error.

The difficulty of minimizing the subtraction error is shown in a paper by Roach, Pettit, Tandberg-Hanssen and Davis [1954] (referred to hereafter as RPTD) in which the authors proceeded by a series of three approximations in their evaluation of the zodiacal light, in each successive approximation attempting to reduce the subtraction error.

In Table 5 we list some published zodiacal light intensities which are compared graphically in Figures 5 and 6. We find the following relationships to hold among the observers:

$$L = 1.455\ R - 20 \qquad (6)$$

$$W = 0.937\ R + 20 \qquad (7)$$

$$E = 0.554\ R - 17 \qquad (8)$$

where L corresponds to intensity as measured by Elvey and Roach [1937] (referred to hereafter as LVR), W by J. Weinberg [1963], E by Elsässer [1958], and R by RPTD [1954]. Although we cannot be certain that the zodiacal light is constant in intensity, we prefer to consider that we here deal with measurement and interpretation differences rather than intrinsic changes. Considering that the measured intensities extend to many hundreds of S_{10} (vis) units, the additive terms of -20, +20 and -17, respectively, which reflect differences of subtraction of the non-zodiacal light components among the observers may be taken as of secondary importance. We are left with the conclusion that the principal cause of the discrepancies is due to differences of absolute calibrations among the observers. One of us (FER) has been directly associated with two of the measurements (LVR and RPTD) separated in time by 17 years and in calibration by a factor of 1.45! As we shall see later, our present results lie between the two earlier investigations.

We now turn to a comparison of the integrated starlight intensities, S, listed by us in Table 2 and those previously reported by Elvey and Roach [1937] and by Elsasser and Haug [1960]. In the case of the LVR measurements, we have read off values of the "galactic light" in S_{10}(ph) units shown by them in their Figure 11 corresponding to the galactic coordinates of the successive zenith observations of the present study. These were converted into S_{10} (vis) units by reversing the original procedure employed by LVR in their estimation of the galactic light.* The Elsässer-Haug (EH) measurements of absolute

---

*In the Appendix A, we explain the conversion from the S_{10}(ph) units used by LVR to the S_{10} (vis) units used in this paper.

Table 5.

Comparison Of Four Independent Zodiacal Light Studies. Brightness In the Ecliptic. In S_{10} (vis) Units

$\lambda - \lambda_{\odot}$	MEASUREMENTS				DEDUCED (Present Study)
	E	JW	RPTD	LVR	
30	1230	2200	2331	-	2740
35		1545	1594	2295	1880
40	630	1130	1184	1691	1390
45		898	945	1323	1110
50	420	730	755	1063	890
55		610	601	864	710
60	270	520	498	719	590
65		445	426	622	500
70	180	385	371	538	440
75		338	329	468	390
80	130	300	297	414	350
85		270	271	371	320
90	110	250	247	329	290
95		228	229	297	270
100		215	211	271	250

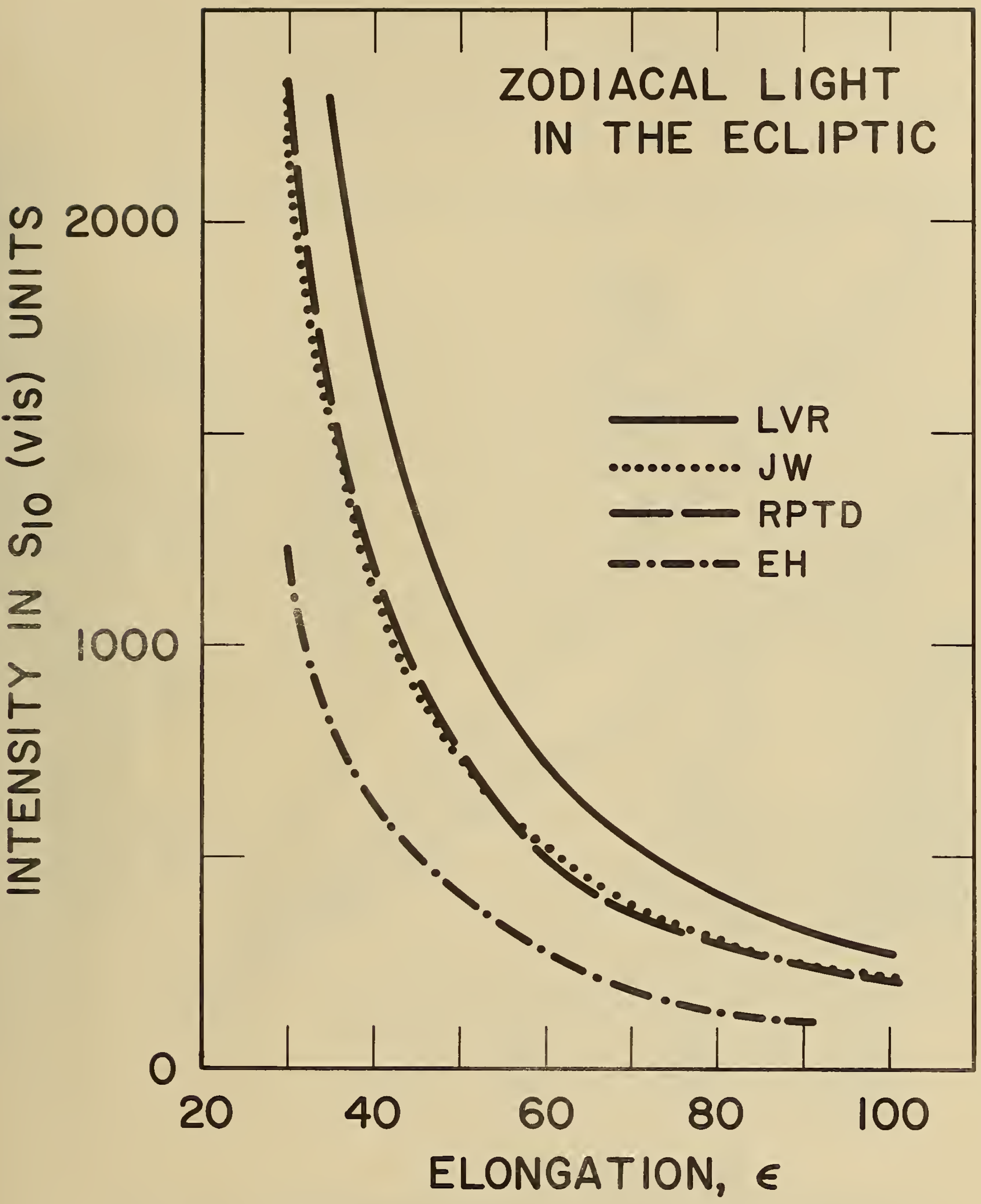

Figure 5. Four independent published plots of the variation of the intensity of the zodiacal light in the ecliptic with elongation angle from the sun (from Table 5).

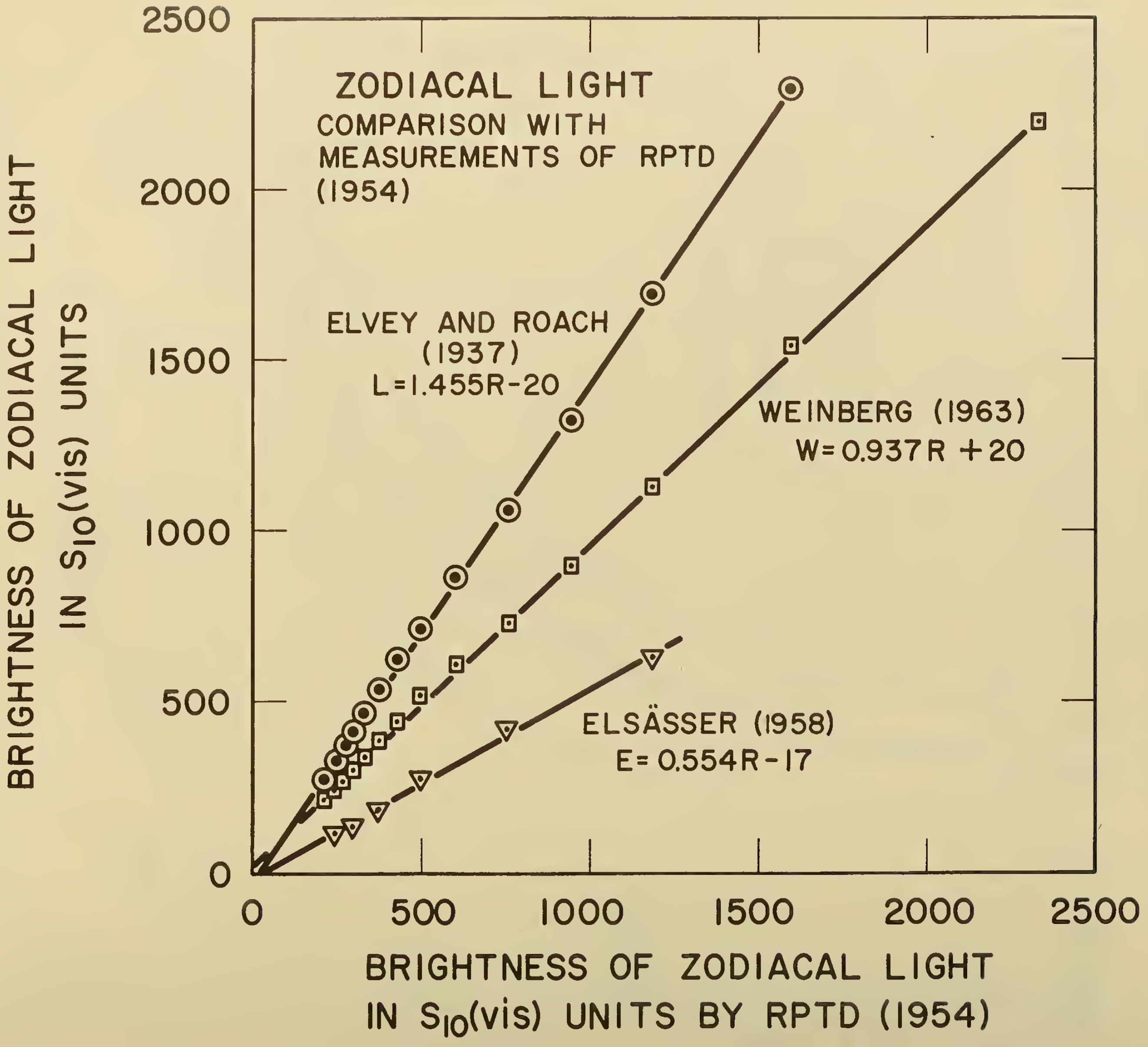

Figure 6. The zodiacal light data of Table 5 and Figure 5 showing the interrelationships of four independent studies.

intensity were taken from their Figure 3, again for each of the galactic coordinates corresponding to our successive zenith readings.

The common observations when plotted showed an obvious correlation but with a scatter that indicated the need of least-squares solutions. We find

$$L = 1.34\ S + 16 \qquad (r = 0.84) \tag{9}$$

$$E = 0.43\ S + 41 \qquad (r = 0.85). \tag{10}$$

We note immediately that the LVR results for the integrated starlight are relatively high and the EH* low, strengthening the conclusion reached in the comparison of zodiacal light results that the two investigations differ because of differences of absolute calibration. The interrelationships are shown graphically in Figure 7. In Table 6, we summarize the relationships among several observers based on both integrated starlight and zodiacal light studies. In the last column a multiplying factor is given to refer the diverse results to the scale of the present paper (RS).

6. THE GALACTIC LIGHT

The discussion in the preceding section on the intercomparison of various investigations on the light of the night sky leads directly to the question of the existence of the so-called "galactic light" which was invoked by Elvey and Roach [1937] to explain the fact that their deduced integrated starlight intensities were systematically higher than those predicted by the star count integrations of Bottlinger [1932]. The indication in the present study that the LVR absolute calibration was systematically high invites examination of the possibility that the

---

*The Elsässer-Haug results for the integrated starlight and the earlier Elsässer results for the zodiacal light are based on similar instrumentation and calibration procedures. In the Elsässer-Haug paper on integrated starlight [1960], the earlier Elsässer [1958] results for the zodiacal light were used.

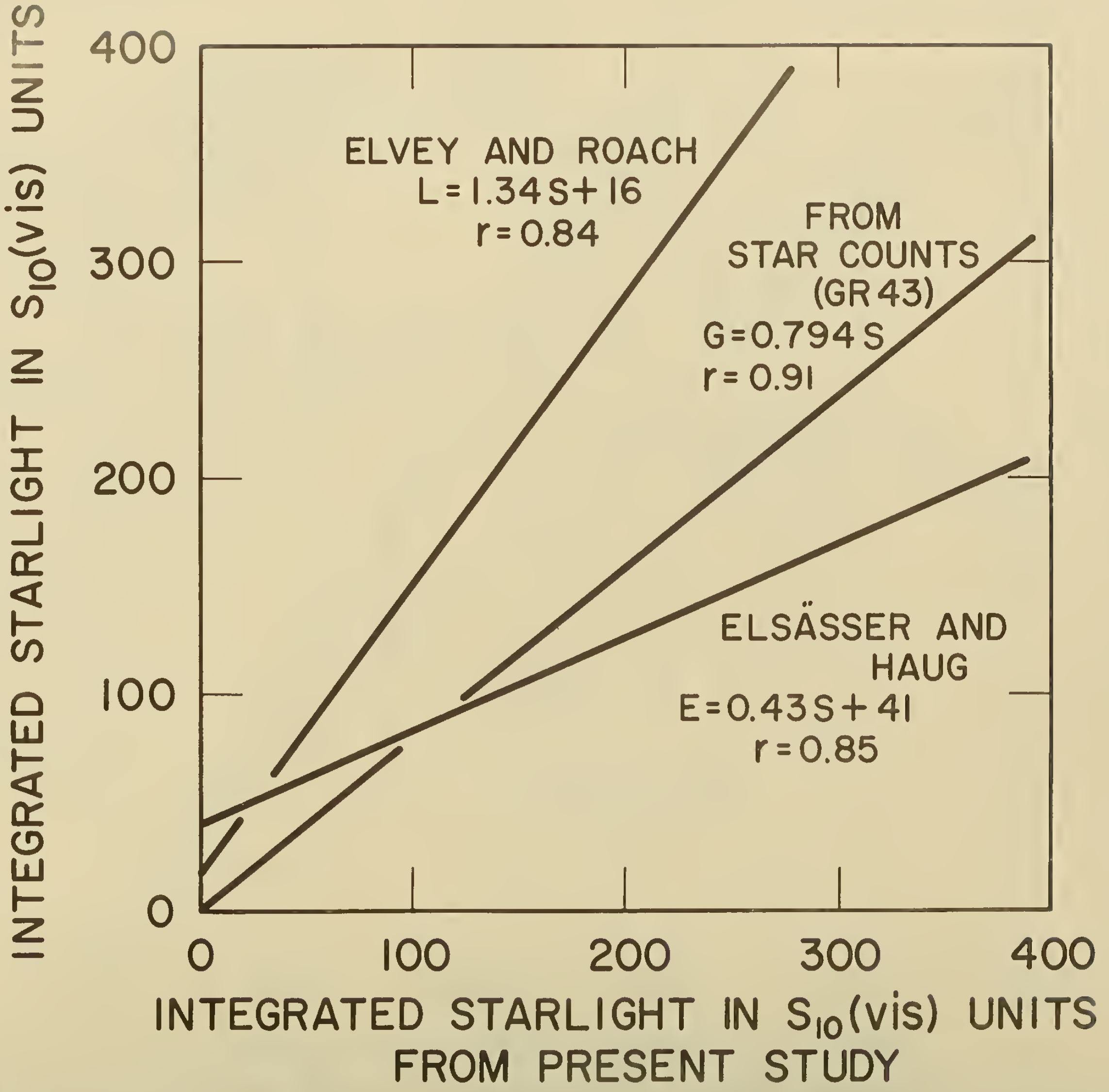

Figure 7. Integrated starlight as observed by LVR and by EH and the computed integrated starlight by van Rhijn (G) plotted against the integrated starlight from the present study. The equation involving G is the reciprocal of eq. (5).

Table 6.

Summary of Relative Calibrations Deduced from Several Published Studies of the Integrated Starlight and the Zodiacal Light.

Relative Intensities (Observed)			Relative Intensities normalized to RS=1.00 and Z.L. results of column 3.			
Investigators*	Integrated Starlight	Zodiacal Light	LVR=1.34	EH=0.43	Mean	Multiplying factor (mean)
EH	0.43	.554	.51	.43	.47	2.13
JW	-	.937	.86	.73	.794	1.26
RPTD	-	1.000	.92	.78	.85	1.18
RS	1.00	-	1.00	1.00	1.00	1.00
LVR	1.34	1.455	1.34	1.13	1.235	.81

*Code for Investigators

EH	Elsässer, 1958 Elsässer and Haug, 1960 Elsässer, 1963
JW	Weinberg, 1963
RPTD	Roach, Pettit, Tandberg-Hanssen and Davis, 1954
RS	Present Study
LVR	Elvey and Roach, 1937

numerical values of the galactic light deduced by them should be significantly reduced, possibly to zero.

In the opposite direction, the integrated starlight intensities reported by Elsässer and Haug [1960] are systematically lower than those predicted by the star counts of GR 43* which, in the absence of an error in absolute calibration, could only occur if there is a systematic error in the star counts themselves. The relationship between the EH measurements (E) and the GR 43 integrations (G) found by us from the entire Milky Way is

$$E = 0.40\ G + 72 \qquad (r = 0.71) \qquad (11)$$

Also

$$E' = 0.43\ G + 81 \qquad (r = 0.74) \qquad (12)$$

$$E'' = 0.45\ G + 87 \qquad (r = 0.75) \qquad (13)$$

where E' corresponds to the Elsässer-Haug measurements increased by light from magnitudes 6 and 7** and E" from magnitudes 6, 7 and 8.

In our previous discussion, we have presented circumstantial evidence that suggests that the three investigators, LVR, EH and RS are in disagreement with respect to their absolute calibrations (multiplying error) and their allowances for airglow plus zodiacal light (subtracting error). Without passing judgment on which of the three may be most nearly correct, it is obvious that the galactic light deductions from the three must be in serious divergence.

A critical matter, as brought out by Henyey and Greenstein [1941], is the wide divergence in the integrated starlight deduced from star counts as reported in the literature. Comparing the integrated starlight deduced from tables of star counts by Seares and Joyner [1928]

---

*The Elsässer-Haug intensities agree numerically with the star count integrations of Bottlinger. The Bottlinger integrations based on the star counts of Mt. Wilson Contribution 301 (Seares, et al. [1925]) and those based on GR 43 star counts are in systematic disagreement at low galactic latitude.

**Elsässer and Haug estimated that their photometer recorded stars brighter than magnitude 8 as individual stars. Included in the GR 43 integration as used, were stars from magnitude 6.

and by van Rhijn (GR 43) they found* that, for galactic latitude 0°,

$$S_{10}\ (\text{phot}) = 121 \qquad (\text{Seares and Joyner})$$

$$S_{10}\ (\text{phot}) = 201 \qquad (\text{van Rhijn})$$

In order to illustrate the dependence of an estimation of the galactic light on the several uncertainties in the analysis, it is convenient to recall that

$$\text{Galactic light} = \text{Total light} - (\text{airglow} + \text{zodiacal light} + \text{integrated starlight}).$$

The numerical values of the galactic light that have been reported are in the range 10 to 100 S_{10} (phot) units. A typical zenith total light reading in the Milky Way is 250, of the zodiacal light 60, and of the airglow 30. For the two values of integrated starlight cited, we thus obtain

$$\begin{aligned}\text{Galactic light} &= 250 - (30 + 60 + 201) = -41\\ \text{or} &= 250 - (30 + 60 + 121) = +39.\end{aligned}$$

It is obvious that the uncertainty in our knowledge of the integrated starlight will make an estimation of galactic light extremely difficult. When one adds to the problem of absolute calibration the difficulty of subtracting out the airglow and zodiacal light, it is apparent that <u>all</u> galactic light estimates should be considered as provisional.

We know of four independent estimates of the galactic light and show them in Table 7 with two alternate solutions, one based on values of the integrated starlight from Seares, van Rhijn, Joyner and Richmond [1925] and the other on the higher values from GR 43. It is to be noted that the measurements of Henyey and Greenstein [1941] are not subject to a large uncertainty from the integrated starlight term

---

*In the galactic light discussion we use S_{10} (phot) rather than S_{10} (vis) in agreement with most of the literature. For a rough orientation, S_{10} (vis) $\approx$ 2 S_{10} (phot) but see Appendix A for a discussion of the color index and its effect on S_{10} (vis) / S_{10} (phot).

Table 7.

Galactic Light Estimates
for galactic latitude 0
in S_{10} (phot) units

Investigators	Elvey and Roach		Henyey and Greenstein	Elsässer and Haug		Roach and Smith (present study)	
	Direct	Revised		Direct	Revised	1.26XGr.43	1.26XMt.W.301
Measured Brightness	174	141	127	102	201	217	127
Integrated Starlight							
Magnitude range	6.0-∞	6.0-∞	16.0-∞	8.0-∞	8.0-∞	5.0-∞	5.0-∞
(a) Mt W 301	96	96	20	90	90		101
(b) Gron 43	166	166	43	159	159	172	
Galactic light (a)	78	45	107	12	111		26
(b)	8	-25	84	-57	42	45	

because they were able to avoid stars brighter than m (pg) = 16. In addition to the direct observational results by LVR and by EH, we have listed revised values based on the empirical relations found in this study to place their absolute intensities in our system (see Table 6).

The mean galactic light values from Table 7 are 72 S_{10} (phot) referred to the Mt. Wilson 301 star counts and 36 referred to the GR 43 star counts*. A careful study of the literature on the subject of the galactic light was made by van Houten [1961] who used a value of 12 in his analysis.

In order to illustrate both the observational and the computational difficulties of evaluating the galactic light, we have plotted together the observational results** for the zenith of Fritz Peak (Figure 8) and Haleakala (Figure 9) based on LVR, RS and EH together with the predictions from the GR 43 star counts. We note that for the four Milky Way crossings:

LVR $>$ GR 43 for all four crossings

RS $>$ GR 43 for two crossings

RS $\approx$ GR 43 for one crossing

RS $<$ GR 43 for one crossing

EH $<$ GR 43 for all four crossings

7. THE ZODIACAL LIGHT

In our treatment of the mean intensities over a year, we found it convenient to consider that the zodiacal light as observed in the zenith is a function only of the ecliptic latitude, β, according to the entries of Table 3. In an individual observation the zodiacal light component must vary from the mean value. The nature of the variation is apparent from an examination of Figure 10 in which we show an isophote map of

---

*In these means we have used the "revised" values for LVR and EH.

**Note that in Figures 8 and 9 we have used S_{10} (vis) units.

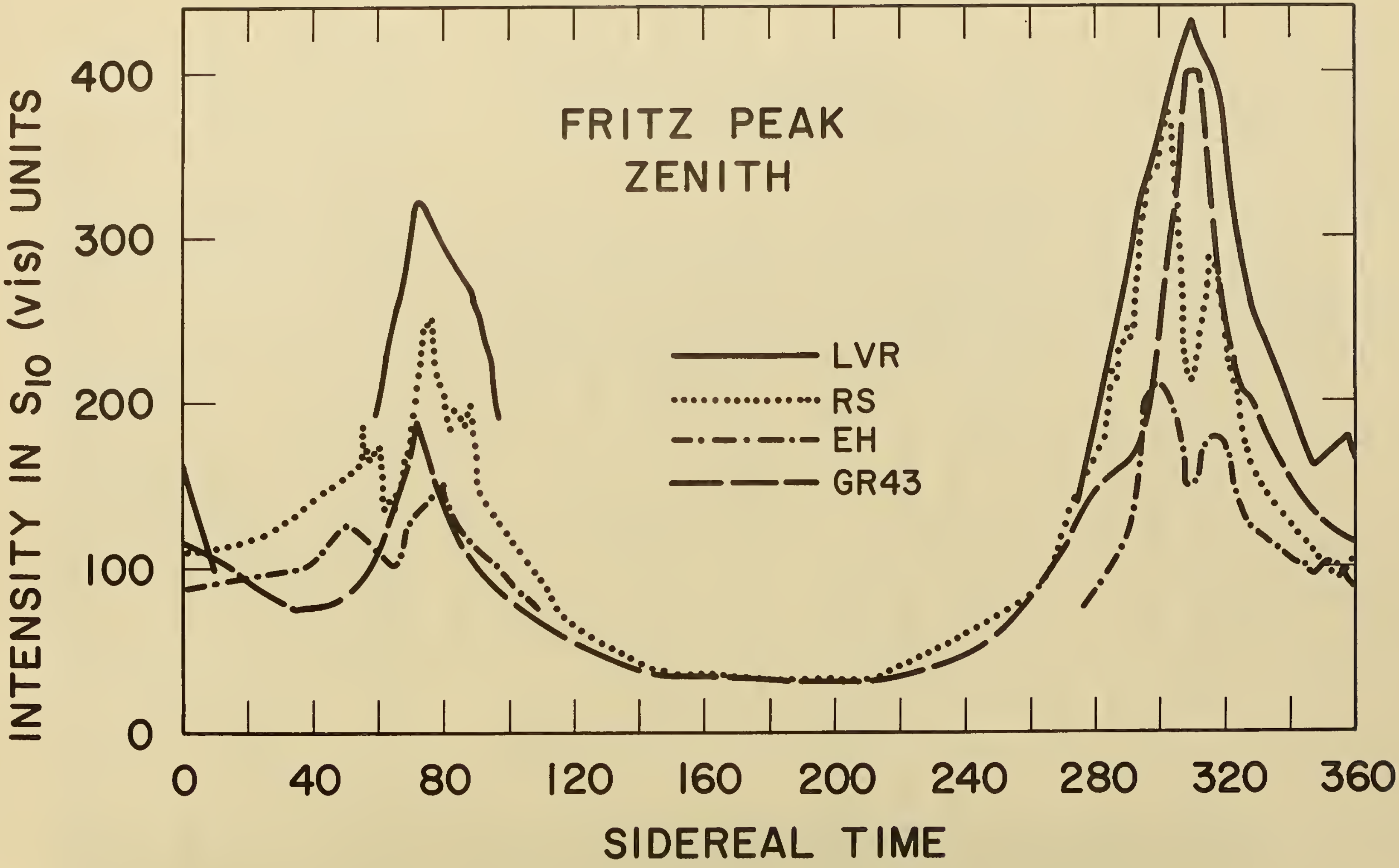

Figure 8. The intensity of the integrated starlight component of the light of the night sky for the zenith of Fritz Peak based on (a) the present study, RS, (b) the observations of Elvey and Roach (LVR), (c) the observations of Elsässer and Haug (EH), and (d) the star counts of van Rhijn, GR 43.

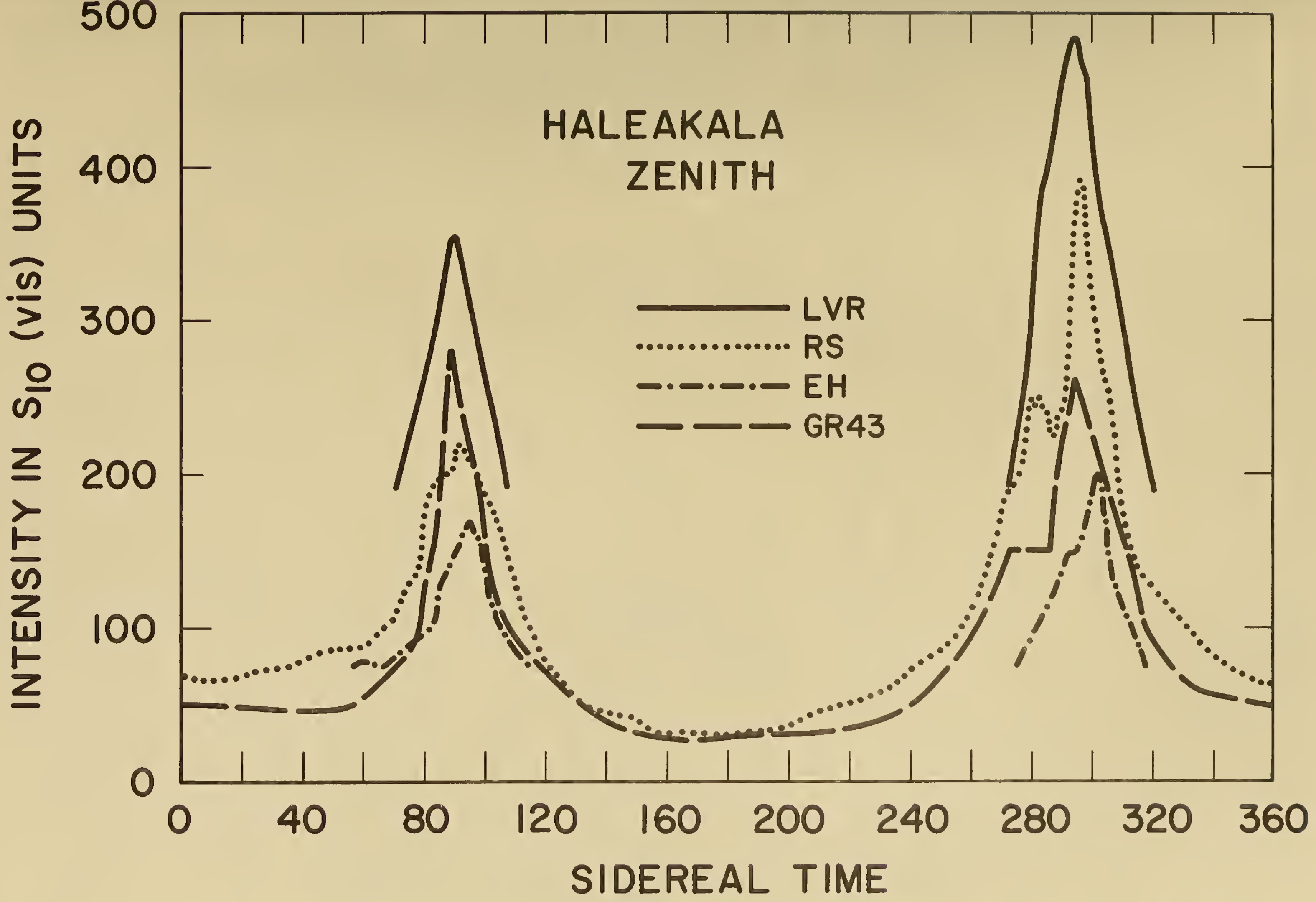

Figure 9. The intensity of the integrated starlight component of the light of the night sky for the zenith of Haleakala based on (a) the present study, RS, (b) the observations of Elvey and Roach (LVR), (c) the observations of Elsässer and Haug (EH), and (d) the star counts of van Rhijn, GR 43.

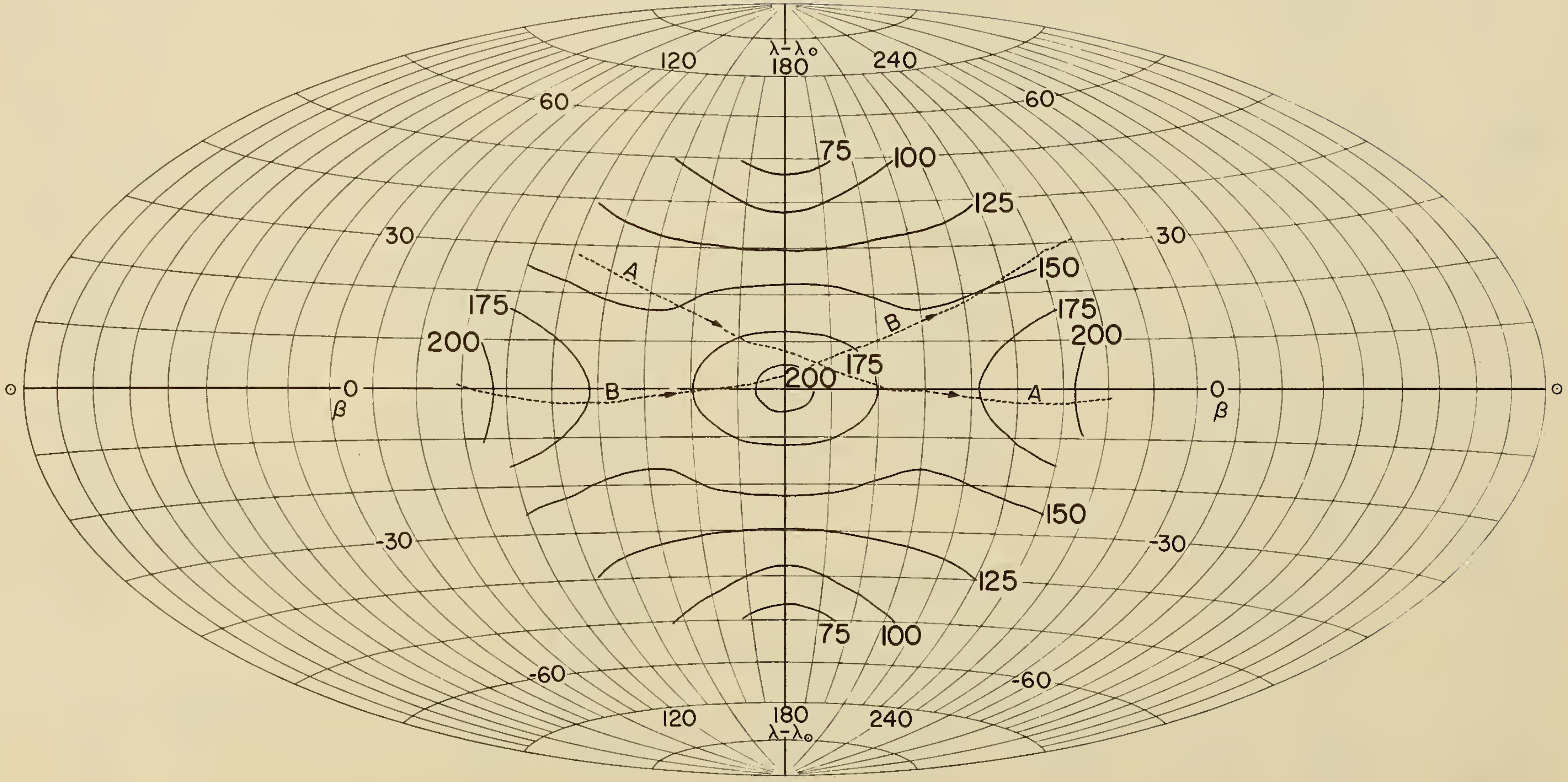

Figure 10. Isophotal map in S_{10}(vis) units of the gegenschein and adjacent zodiacal light in ecliptic coordinates taken from Figure 5 of Roach and Rees [1956]. The locus is shown of the zenith at Haleakala for two nights included in the present study: A, Nov. 6/7, 1961; B, Feb. 3/4, 1962.

the portion of the zodiacal light and gegenschein included in the zenith according to the two coordinates, ecliptic latitude and differential ecliptic longitude*, $\lambda - \lambda_\odot$. It is noted that for any given ecliptic latitude there is a range of intensities with respect to the mean values of Table 3 and that, during a given night, the observation locus includes a variety of $\lambda - \lambda_\odot$ values.

The procedure adopted by us should be a reasonable approximation for the purpose of deducing the integrated starlight from the original mean zenith intensities based on the randomly distributed (with respect to $\lambda - \lambda_\odot$) 15 to 30 individual readings entering into the means. However, for a given observation or for a given night the $\lambda - \lambda_\odot$ term introduces a variation with respect to the mean that is by no means trivial.

The point is illustrated in Figure 11 where we have plotted, for two nights, the individual observations as differences from the over-all means. For comparison we show the zodiacal light differences deduced from the isophote map of Figure 10 in conjunction with the means from Table 3. The parallelism of the two sets of data supports the thesis that there is a significant variation of zenith intensity (referred to our means of Table 3) due to the $\lambda - \lambda_\odot$ term in the zodiacal light. We plan to make definitive studies of this matter in subsequent investigations.

Most of the zodiacal light investigations have dealt with the brighter regions in the ecliptic ($30° < \epsilon < 90°$). Although we have no direct observations of this domain in the present study, we now propose to refer some published results to our photometric scale.

In Table 5, (column 6), we put the diverse results of four independent investigators of the zodiacal light in the ecliptic into the

---

*In the ecliptic $\lambda - \lambda_\odot = \epsilon$, the elongation angle between the line of sight and the sun. Away from the ecliptic $\cos \epsilon = \cos (\lambda - \lambda_\odot) \cos \beta$. Thus, the correct procedure in physical analyses is to use the parameter, ϵ, in conjunction with line-of-sight integrations involving particle density. In the present case, it suffices to present the isophotes as functions of $\lambda - \lambda_\odot$ and β.

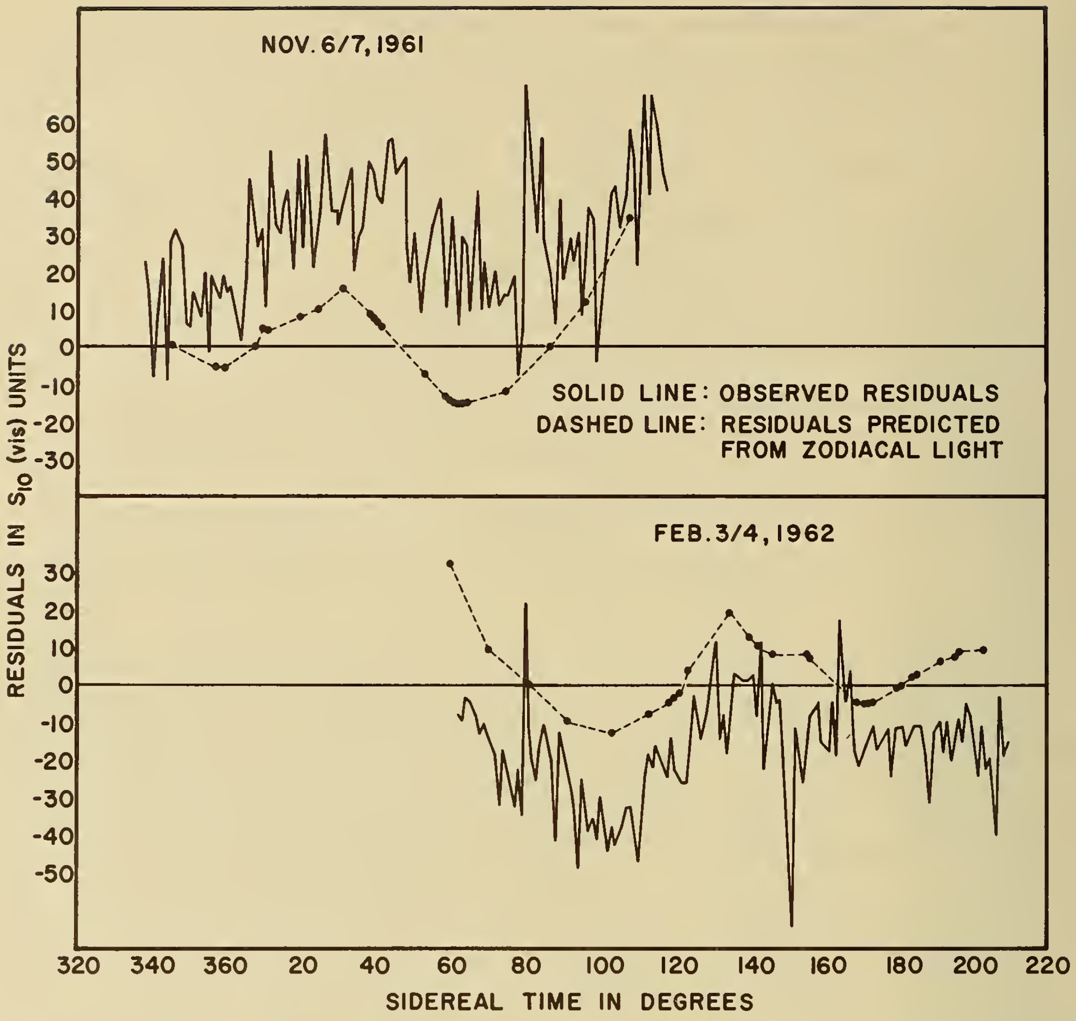

Figure 11. The solid lines represent residuals between the total observed intensities for individual nights and the mean intensities from the ensemble of data of this study. The dashed lines correspond to residuals between the zodiacal light from the isophotal map of Figure 10 and the means as a function of β alone of Table 3. The general trends of the two residual curves parallel each other indicating that the cause is the zodiacal light dependence on $\lambda - \lambda_{\odot}$. The systematic displacement of the curves may be interpreted as due to variations in airglow from night to night. The random scatter of the solid curve is probably chiefly due to instrumental and measurement errors (see Table 8 for a summary of error estimates).

absolute scale of our present study. The resulting intensities constitute a consistent body of data approximately mid-way between the RPTD and LVR results. It should be noted that, if the calibration on which this study is based is in error on the high side by a factor of 1.26, this would (a) eliminate the evidence in our data for galactic light (eq 5) and (b) reduce the zodiacal light intensities to almost exact agreement with those recently reported by Weinberg [1963] (Table 6).

The entries of column 6 of Table 5 lead to interesting relationships between the intensity of the zodiacal light and the elongation from the sun, ϵ, in degrees. For the three cases: (a) the corona F, (b) the interpolation between the corona F and the observed zodiacal light of this study, and (c) the zodiacal light, we find in units* of H and H'

$$\text{Corona F} : \quad \begin{array}{l} \log H = 6.36 - 2.5 \log \epsilon \quad \text{or} \\ \log H' = 6.22 - 2.5 \log \epsilon \end{array} \tag{14}$$

$$\text{Interpolation} : \quad \begin{array}{l} \log H = 6.37 - 2.24 \log \epsilon \quad \text{or} \\ \log H' = 6.23 - 2.24 \log \epsilon \end{array} \tag{15}$$

$$\text{Zodiacal Light} : \quad \begin{array}{l} \log H = 6.34 - 2.20 \log \epsilon \quad \text{or} \\ \log H' = 6.20 - 2.20 \log \epsilon \end{array} \tag{16}$$

The similarity in the log H - log ϵ relationships for the three regions has often been mentioned in the literature (see for example equations (3), (4) and (5) of RPTD [1954]). The three curves merge so smoothly into each other that it has encouraged investigators to examine the interpolation region to test the hypothesis that the F corona and the zodiacal light are parts of the same physical phenomenon (see e.g. Figure 7 in the paper by Blackwell and Ingham [1961]). Interpretations of the zodiacal light in terms of the physical composition of the interplanetary medium have resulted in several papers over the past two decades starting with the classical papers by van de Hulst [1947] and by Allen [1946]. Such analyses depend on knowledge of both the intensity

---

*See Appendix A for a discussion of units.

and the polarization characteristics of the zodiacal light. The present paper is concerned with only the intensity. For a definitive study of the polarization, the reader is referred to a recent paper by Weinberg [1963]. In addition to an exposition of the polarization Weinberg has included a useful bibliography of zodiacal light papers.

8. SUMMARY AND CONCLUSIONS

Our motivation in this study was two-fold: (1) to attempt a summary and discussion of divergent photometric observations of the so-called light of the night sky, and (2) to provide a list of absolute intensities of specific regions of the sky which can serve as "standard light sources" for ourselves and other investigators in future studies.

The use of the total intensities in Table 2 as standard light sources should be tempered by the following considerations:

(1) They can be used in the zenith only at latitudes equal to those of Haleakala (N 20.7°) and Fritz Peak (N 39.9°), but they are potentially useful for other latitudes for observations "off zenith."

(2) A random observation will not agree exactly with the tabulated value due to the possible variation of the airglow. It should be noted that, although we were able to assume constancy of the airglow with respect to sidereal time, sporadic changes in the airglow or systematic changes with respect to local times are likely to occur.

(3) A random observation will not agree with the tabulated value due to the fact that the zodiacal light intensity is a function not only of the ecliptic latitude as given in Table 3 but also of the differential longitude, $\lambda - \lambda_{\odot}$, from the sun. This was treated in Section 7.

(4) There are inherent errors of an instrumental or measurement nature.

(5) The evaluation of the two sources of fluctuation mentioned in (2) and (3) above is consistent with the computed probable errors of the means. We used about 25 individual observations for the mean

intensities for each sidereal time in the case of Haleakala. The probable error of the mean was about 4 S_{10} (vis) units. The probable error of a single observation is therefore about 20 S_{10} (vis) units. We show in Table 8 a summary of our estimates of the probable errors due to the three contributors.

(6) Although the observations for the two stations constitute internally consistent ensembles, it is necessary to keep in mind that the absolute accuracy of the entries in Table 2 is not as good as that implied by the probable errors based on the scatter of our individual observations.

We estimate that the total intensities listed in Table 2 are accurate to ± 10% which implies better than ± 10% absolute accuracy for the laboratory calibrations of the standard lights in our photometers. This estimate is consistent with the fact that the Haleakala and Fritz Peak correlations with the GR 43 star count integrations [eq (3) and (4)] differ by about 10%. Recently we have installed, in the photometers of both stations, new standard lights which have been given independent laboratory calibrations. It is hoped that a year of observations with the new standard lights will yield improved data.

We are of the opinion that the principal cause of the inaccurate calibrations that have plagued many investigators over the years has been the difficulty attendant on the use of star crossings. This point is discussed in some detail in Appendix B.

ACKNOWLEDGMENTS

We are indebted to our colleagues in the Airglow and Aurora Section of the Central Radio Propagation Laboratory of the National Bureau of Standards for invaluable assistance in the acquisition of the observations under analysis in this paper. We wish also to thank Professor Walter Steiger of the University of Hawaii for his cooperation and assistance in the procuring of the data on Haleakala and for inviting us to the Hawaii Institute of Geophysics for the academic year 1963-64. We have been stimulated by many conversations with our

Table 8.

Estimated Probable Errors

in S_{10} (vis) units.

Source	25 Mean of Observations	One Random Observation
Instrumental and Measurement Errors	1.2	6
Zodiacal light variations	3	15
Airglow variations	2	10
Total (effective)	4	19

colleagues, Dr. J. Weinberg and Dr. M. Huruhata. One of us (FER) gratefully acknowledges the opportunity to work in Hawaii by the award of a 1963-64 Senior Specialist Award at the East-West Center of the University of Hawaii. Finally, a significant part of the financing of the project has been through NASA grant R-18.

APPENDIX A

ABSOLUTE UNITS IN NIGHT SKY PHOTOMETRY

The units used in surface photometry are a source of some confusion to the casual reader. We propose to define the units which seem to us to be appropriate in studies of the light of the night sky and to show their inter-relationships.

A general rule in the selection of a unit for a particular application is based upon the rapidly growing use of digital computer techniques. We have found that, in observational problems, the use of three significant digits is optimum— two digits is frequently too coarse and four digits almost always too fine. In our punched card formats, we have standardized for several years on three-digit fields. As a matter of convenience, it is desirable that the unit be chosen so that there is no decimal point for the bulk of the data, thus the entries are included in the 001 to 999 range.

With these general considerations in mind, we recommend the following units:

(1) For integrated starlight: S_{10} (vis), the number of 10th magnitude (visual) stars per square degree of sky. The unit is a natural one since its evaluation is based on the traditional practice of astronomers to express star counts in terms of number of stars per square degree of sky. Star counts have been based on the photographic magnitude scale rather than the visual, and we prefer to convert to the visual scale because its effective wavelength is very close to the 5300 A filter used in the present study. The conversion may be made from the color index (CI) by the formula

$$S_{10}\ (\text{vis}) = S_{10}\ (\text{phot}) \times 10^{0.4\ \text{CI}} .$$

The color index of the sun may be taken as 0.57, thus for any surface corresponding to the sun in color, for example, the zodiacal light,

$$S_{10}\ (\text{vis}) \,/\, S_{10}\ (\text{phot}) = 1.69 .$$

The color index of the stars in general changes systematically with the apparent magnitude — the fainter stars are statistically redder (larger positive color index). The integrated starlight depends more and more on fainter stars as the galactic plane is approached. The effective color index at the galactic pole is about 0.7 (S_{10} (vis) / S_{10} (phot) = 1.9) and at the galactic equator about 0.8 (S_{10} (vis) / S_{10} (phot) = 2.1). This variation of effective color of integrated starlight with galactic latitude was used by us in converting the LVR results published in S_{10} (phot) units to our present scale in S_{10} (vis) units.

(2) For zodiacal light: H, 10^{-15} times the mean radiance of the sun is recommended. This is a natural unit since the zodiacal light is the result of sunlight on interplanetary particles.*

(3) For airglow "continuous" emissions: R/100 A = rayleighs per 100 Angstroms is recommended. The rayleigh has been internationally adopted as a unit for upper atmosphere emissions [Hunten, Roach and Chamberlain, 1956]. It is a natural unit since it is easily referred to the rate of quantal production in upper-atmosphere layers. If the radiance, B, is measured in 10^6 quanta · cm^{-2} · sec^{-1} · $steradian^{-1}$ the total flux in rayleighs, R, is $4\pi B$** or $1R = 10^6$ quanta · cm^{-2} · sec^{-1} · $sphere^{-1}$. Since the effective thickness of an upper atmosphere layer is frequently approximately 10 km = 10^6 cm, the intensity in rayleighs is approximately equal to the number of quanta · cm^{-3} · sec^{-1} within the emitting layer. If the upper atmosphere light source is not a discrete

---

*Attention is called to an earlier paper [RPTD, 1954] in which a unit $H' = 10^{-15}$ the radiance at the center of the sun was used. For a wavelength of 5300 A, $B_\odot$ (center) = $1.37\ B_\odot$ (mean) and, therefore, $H = 1.37\ H'$.

**Probably a better statement is that, if B_λ is the specific radiance in 10^6 quanta · cm^{-2} · sec^{-1} · $ster^{-1}$ · $Å^{-1}$, then $B = \int_0^\infty B_\lambda d_\lambda$ over the emission line (or over the domain of a filter in the case of a continuum and the total flux in rayleighs = $4\pi B = 4\pi \int_0^\infty B_\lambda d_\lambda$).

emission but is of a continuous nature, we use rayleighs/100 Angstroms (R/100 A) as a unit of specific intensity.

The interrelations among the units mentioned in this Appendix are shown in Table 9.

Table 9.

Relationship of Units for 5300 A

R/100A	B	S_{10} (vis)	H'	H	$m\mu L$
Rayleighs per 100 Angstroms	Ergs cm.$^{-2}$sec.$^{-1}$ A^{-1} ster.$^{-1}$	Number of 10th magnitude visual stars per square degree	10^{-15}x brightness of center of sun	10^{-15}x integrated surface brightness of the sun	Milli-micro lamberts
1	= 2.98×10^{-9}	= 2.27	= 0.752	= 1.03	= 2.20
3.36×10^{8}	= 1	= 7.63×10^{8}	= 2.53×10^{8}	= 3.46×10^{8}	= 7.39×10^{8}
0.440	= 1.31×10^{-9}	= 1	= 0.332	= 0.455	= 0.968
1.33	= 3.95×10^{-9}	= 3.01	= 1	= 1.37	= 2.92
0.968	= 2.88×10^{-9}	= 2.20	= 0.730	= 1	= 2.13
0.455	= 1.35×10^{-9}	= 1.03	= 0.342	= 0.469	= 1

APPENDIX B

THE ABSOLUTE CALIBRATION

It is obvious that the absolute calibration of a photometer is critical in drawing conclusions, for example, as to the existence of the galactic light. The reader has reason to be disturbed that photoelectric photometry with its extraordinarily high precision when applied to such problems as eclipsing binary systems should yield such diverse results in applications to the light of the night sky as those reported by Elvey and Roach [1937] on the one hand and by Elsässer and Haug [1960] on the other. The difficulties seem to be that (1) we deal with very low light levels for which good field standards are not readily available, (2) we are concerned with surface photometry and use relatively large angular circles of sky and, (3) we are striving for absolute accuracy which is more difficult to attain than relative precision such as used in conventional stellar photometry.

We have been preoccupied with the problem of the absolute accuracy of our observations for several years and the present calibration is based on a serious attempt to solve the problem in our field applications. In our laboratory at the Fritz Peak Observatory, we have installed as our primary standard a black body which illuminates a magnesium oxide screen. Secondary standards of fluorescent material irradiated by radioactive material which can be transported to the field are regularly compared with the laboratory black body. Finally, tertiary standards, also of fluorescent material irradiated by radioactive material are built into our photometers in such a way that every sky reading is directly compared with a standard light reading, thus minimizing the effect of transient electrical variations in the amplifier and recording network.*

---

*For a detailed discussion of the procedures followed at the Fritz Peak Observatory in the use of fluorescent standard lights, the reader is referred to Smith and Alexander [1963].

The use of calibration stars of known apparent magnitude has been widely practiced especially since, in routine observing programs, many star crossings may occur. A practical difficulty arises in that, with the large fields (1° to 5° in diameter) used in typical light-of-the-night-sky photometers, the star deflection may depend on the part of the photo-cathode illuminated. This is especially true in the case of the RCA 931 A (1P21) photomultiplier which has a highly sensitive region near the central line of the cathode. Two procedures have been followed to allow for this effect. One may make a multiplicity of star deflection readings essentially mapping out or averaging the sensitivity field of the cathode. This procedure was followed by RPTD [1954] in their study of the zodiacal light. A second method is to use "Fabry optics" to focus the telescope objective on the cathode. This has the effect of spreading a point source out into a disc which, in perfect optics, will be of uniform intensity and independent of the position of the point source (such as a star) in the field. Our experience has been that Fabry optics do significantly improve the reproducibility of stellar deflections but do not completely eliminate errors as will now be shown.

The design of the zenith photometers used in the present investigation includes Fabry optics in conjunction with a 1P21 photomultiplier with the Haleakala telescope and an end-on photomultiplier at Fritz Peak. An inspection of Figure 2 shows that the star crossings are much more conspicuous with the 1P21 photomultiplier (Haleakala) than with the end-on tube (Fritz Peak). Obviously great care would have to be exercised in using the stellar deflections for calibration purposes.

We think the matter is of sufficient importance to justify a numerical example. In Figure 12 we show a plot of the deflections of the bright star Arcturus ($m_V = 0.24$) which goes through the Haleakala zenith and Vega ($m_V = 0.14$) which goes through the Fritz Peak zenith. The deflections are given as S_{10} (vis) units based on the calibrations adopted by us in connection with our calibrated built-in standard lights. The stellar deflection corresponding to our calibration is indicated on the plots. It is noted that in both cases the <u>peak</u>

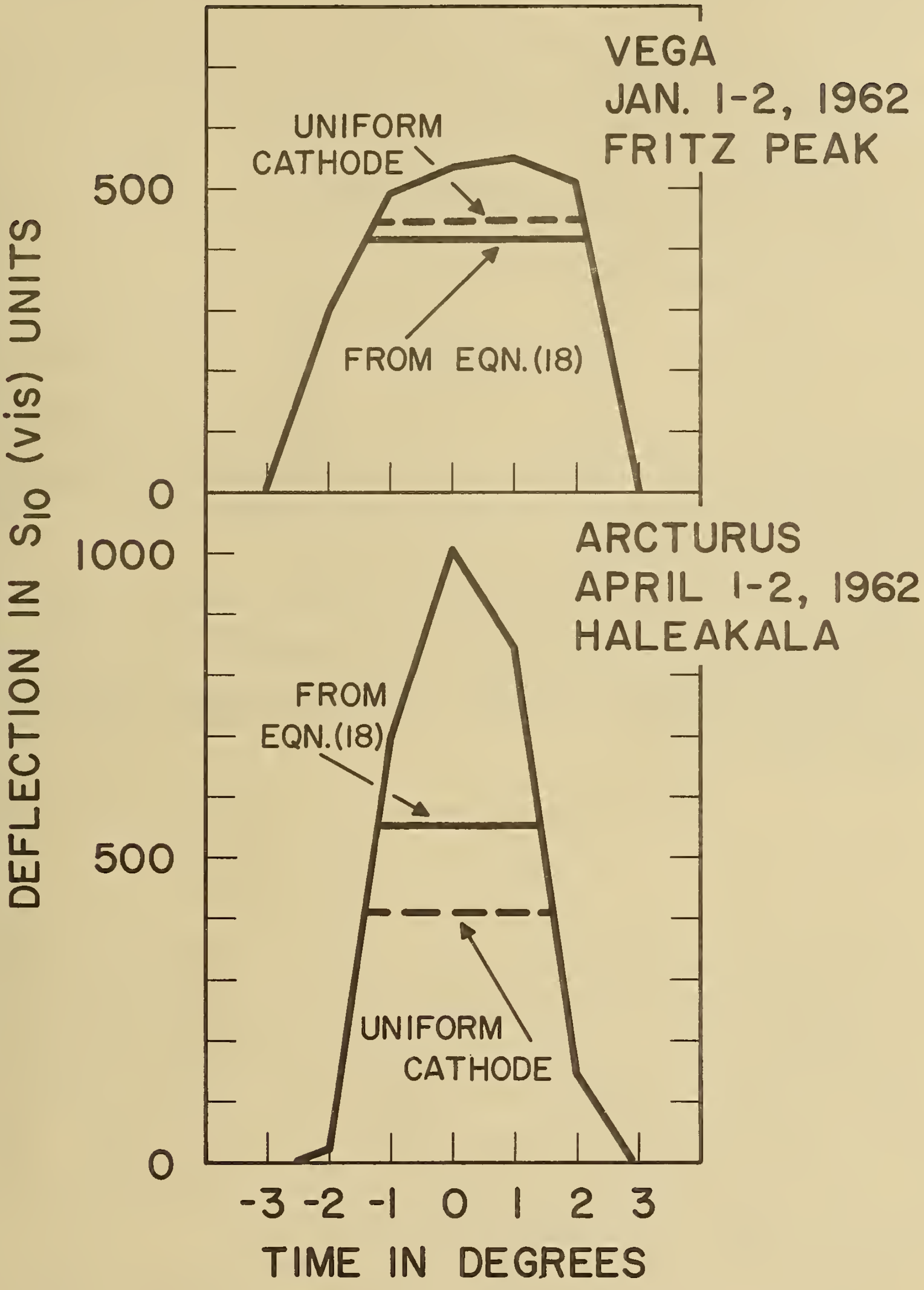

Figure 12. Typical time plots of the deflections due to bright stars going through the field of the zenith photometer. The deflection corresponding to an integration of the entire curve is based on eq. (18). The "uniform cathode" line indicates the steady deflection that would result from perfect optics in conjunction with a photomultiplier with a cathode having uniform sensitivity (eq. 19).

deflection is greater than would have been expected on the basis of our calibration.

Let D be the deflection due to a star, θ the sidereal time. Then the area, A, of a $D - \theta$ plot is

$$A = \int_0^\infty D(\theta)\, d\theta \tag{17}$$

and the $\bar{D}$ corresponding to the star is

$$\bar{D} = \frac{A}{\theta_2 - \theta_1} \tag{18}$$

$\theta_2 - \theta_1$ depends on the latitude of the observer and the portion of the field traversed by the star. For Vega at Fritz Peak, $\theta_2 - \theta_1 = 5.^\circ72$ and for Arcturus at Haleakala, $\theta_2 - \theta_1 = 4.^\circ87$.

The value of $\bar{D}$ from eq (18) can be compared with that based on the apparent magnitude of the star m_v and the photometer field (19.6 square degrees) on the assumption that the cathode is uniformly sensitive. The pertinent relationship is

$$\begin{aligned} \log \bar{D} &= 0.4\,(10.00 - m_v) - \log 19.6 \\ &= 0.4\,(10.00 - m_v) - 1.29\,. \end{aligned} \tag{19}$$

In Figure 12 and Table 10, values of D max and $\bar{D}$ from eq (18) and (19) are compared. We conclude: (a) The use of the peak deflection can give calibration errors as great as 2 for the 1P21 tube and (b) star crossings can yield reasonable calibrations if allowance is made for the variable sensitivity of the cathode surface by way of eq (18). The sense of the error resulting from the use of peak deflections is such that deduced surface brightnesses will be too small.

In spite of the efforts we have made in this study to achieve good calibrations, we consider that the absolute accuracy of our present results may be no better than ± 10%. In contrast with this somewhat pessimistic estimate, we found that the probable errors of the means in

Table 10.

D (Star)	Vega (F.P. end on)	Arcturus (Haleakala, 1P21)
From max. D	550	1007
From Eq (18)	413	552
From Eq (19)	448	409

the columns headed "total" in Table 2 were about 4 S_{10} (vis) units ($\sim$1-1/3%) for Haleakala and 5 S_{10} (vis) units ($\sim$1-1/2%) for Fritz Peak. Thus the intensities for the two stations constitute internally self-consistent sets of data which can be used with confidence by future investigators at the same latitudes even though they may be found to require systematic absolute corrections.

It seems necessary to reiterate what was earlier pointed out in the discussion of the galactic light, namely that the uncertainties and difficulties associated with absolute calibrations of photometers, compounded by the uncertainty in the integrated starlight deduced from star counts dictate a cautious and even skeptical attitude toward the acceptance of the reality of the existence of the galactic light. The uncertainty should probably be resolved by investigations with meticulously calibrated photoelectric photometers attached to astronomical telescopes. Such a set-up using a very small field of view could, by avoiding the bright stars which contribute most of the integrated starlight, minimize the uncertainty due to the interpretation of star counts. However, the problems of absolute calibration and of subtracting out zodiacal light and airglow remain.

REFERENCES

Allen, C. W. (1946), Monthly Notices Roy. Astron. Soc. 106, 137.

Barbier, D. (1955), Mem. Soc. Roy. Sci. Liege 15, 55.

Blackwell, D. E., and M. F. Ingham (1961), Monthly Notices Roy. Astron. Soc. 122, 113.

Bottlinger, K. F. (1932), Z. Astrophys. 4, 370.

Elsässer, H. (1958), Die Sterne 34, 166.

Elsässer, H. (1963), Planetary Space Sci. 11, 1015.

Elsässer, H., and U. Haug (1960), Z. Astrophys. 50, 121.

Elvey, C. T., and F. E. Roach (1937), Astrophys. J. 85, 213.

Henyey, L. G., and J. L. Greenstein (1941), Astrophys. J. 93, 70.

Hunten, D. M., F. E. Roach, and J. W. Chamberlain (1956), J. Atmospheric Terrest. Phys. 8, 345.

Purdy, C. M., L. R. Megill, and F. E. Roach (1961), J. Res. Natl. Bur. Stds. 65C, 213.

Roach, F. E., and L. R. Megill (1961), Astrophys. J. 133, 228.

Roach, F. E., and H. B. Pettit (1951), J. Geophys. Res. 56, 325.

Roach, F. E., H. B. Pettit, E. Tandberg-Hanssen, and D. N. Davis (1954), Astrophys. J. 119, 253.

Roach, F. E., and M. H. Rees (1956), The Airglow and the Aurorae, p. 142, Pergamon Press, London.

Seares, F. H., and M. C. Joyner (1928), Astrophys. J. 67, 24.

Seares, F. H., P. J. van Rhijn, M. C. Joyner, and M. L. Richmond (1925), Astrophys. J. 62, 320.

Smith, L. L., and R. B. Alexander (1963), IQSY Secretariat, London, No. 5, p. 25.

van de Hulst, H. C. (1947), Astrophys. J. 105, 471.

van Houten, C. J. (1961), Bull. Astron. Instit. Netherlands 16, No. 509.

van Rhijn, P. J. (1925), Groningen Pub. No. 43.

Weinberg, J. L. (1963), PhD. dissertation, University of Colorado.

GPO 842-421

DEPARTMENT OF COMMERCE ★ UNITED STATES OF AMERICA ★