

HARVARD OBSERVATORY MONOGRAPHS

HARLOW SHAPLEY, EDITOR

No. 1

STELLAR ATMOSPHERES

A CONTRIBUTION TO THE OBSERVATIONAL
STUDY OF HIGH TEMPERATURE IN THE
REVERSING LAYERS OF STARS

BY

CECILIA H. PAYNE

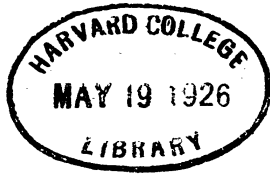
PUBLISHED BY THE OBSERVATORY

CAMBRIDGE, MASSACHUSETTS

1925

△

Astr 6809.25



Sara Chase Smith

COPYRIGHT, 1925
BY HARVARD OBSERVATORY

PRINTED AT THE HARVARD UNIVERSITY PRESS
CAMBRIDGE, MASS., U. S. A.

EDITOR'S FOREWORD

THE most effective way of publishing the results of astronomical investigations is clearly dependent on the nature and scope of each particular research. The Harvard Observatory has used various forms. Nearly a hundred volumes of *Annals* contain, for the most part, tabular material presenting observational results on the positions, photometry, and spectroscopy of stars, nebulae, and planets. Shorter investigations have been reported in *Circulars*, *Bulletins*, and in current scientific journals from which Reprints are obtained and issued serially.

It now appears that a few extensive investigations of a somewhat monographic nature can be most conveniently presented as books, the first of which is the present special analysis of stellar spectra by Miss Payne. Other volumes in this series, it is hoped, will be issued during the next few years, each dealing with a subject in which a large amount of original investigation is being carried on at this observatory.

The Monographs will differ in another respect from all the publications previously issued from the Harvard Observatory — they cannot be distributed gratis to observatories and other interested scientific institutions. It is planned, however, to cover a part of the expenses of publication with special funds and to sell the volumes at less than the cost of production.

The varied problems of stellar atmospheres are particularly suited to the comprehensive treatment here given. They involve investigations of critical potentials, spectral classification, stellar temperatures, the abundance of elements, and the far-reaching theories of thermal ionization as developed in the last few years by Saha and by Fowler and Milne. Some problems of special interest to chemists and physicists are considered, and subjects intimately bound up with inquiries concerning stellar evolution come under discussion.

The work is believed to be fairly complete from the bibliographic standpoint, for Miss Payne has endeavored throughout to give a synopsis of the relevant contributions by various investigators. Her own contributions enter all chapters and form a considerable portion of Parts II and III.

It should be remembered that the interpretation of stellar spectra from the standpoint of thermal ionization is new and the methods employed are as yet relatively primitive. We are only at the beginning of the astronomical application of the methods arising from the newer analyses of atoms. Hence we must expect (and endeavor to provide) that a study such as is presented here will promptly need revision and extension in many places. Nevertheless, as it stands, it shows the current state of the general problem, and will also serve, we hope, as a summary of past investigations and an indication of the direction to go in the immediate future.

In the course of her investigation of stellar atmospheres, Miss Payne has had the advantage of conferences with Professors Russell and Stewart of Princeton University and Professor Saunders of Harvard University, as well as with various members of the Harvard Observatory staff.

The book has been accepted as a thesis fulfilling the requirements for the degree of Doctor of Philosophy in Radcliffe College.

H. S.

MAY 1, 1925.

CONTENTS

PART I

THE PHYSICAL GROUNDWORK

I. THE LABORATORY BASIS OF ASTROPHYSICS	3
Relation of physics to astrophysics.	
Properties of matter associated with nuclear structure.	
Arrangement of extra-nuclear electrons.	
Critical potentials.	
Duration of atomic states.	
Relative probabilities of atomic states.	
Effect on the spectrum of conditions at the source.	
(a) Temperature class.	
(b) Pressure effects.	
(c) Zeemann effect.	
(d) Stark effect.	
II. THE STELLAR TEMPERATURE SCALE	27
Definitions.	
The mean temperature scale.	
Temperatures of individual stars.	
Differences in temperature between giants and dwarfs.	
The temperature scale based on ionization.	
III. PRESSURES IN STELLAR ATMOSPHERES	34
Range in stellar pressures.	
Measures of pressure in the reversing layer.	
(a) Pressure shifts of spectral lines.	
(b) Sharpness of lines.	
(c) Widths of lines.	
(d) Flash spectrum.	
(e) Equilibrium of outer layers of the sun.	
(f) Observed limit of the Balmer series.	
(g) Ionization phenomena.	
IV. THE SOURCE AND COMPOSITION OF THE STELLAR SPECTRUM .	46
General appearance of the stellar spectrum.	
Descriptive definitions.	
The continuous background.	
The reversing layer.	
Emission lines.	
V. ELEMENTS AND COMPOUNDS IN STELLAR ATMOSPHERES . . .	55
Identifications with laboratory spectra.	
Occurrence and behavior of known lines in stellar spectra.	

PART II

THEORY OF THERMAL IONIZATION

- VI. THE HIGH-TEMPERATURE ABSORPTION SPECTRUM OF A GAS . . . 91
- The schematic reversing layer.
 - The absorption of radiation.
 - Low temperature conditions.
 - Ultimate lines.
 - Ionization.
 - Production of subordinate lines.
 - Lines of ionized atoms.
 - Summary.
- VII. CRITICAL DISCUSSION OF IONIZATION THEORY. 105
- Saha's treatment — marginal appearance.
 - Theoretical formulae.
 - Physical constants required by the formulae.
 - Assumptions necessary for the application.
 - Laboratory evidence bearing on the theory.
 - (a) Ultimate lines.
 - (b) Temperature classes.
 - (c) Furnace experiments.
 - (d) Conductivity of flames.
 - Solar intensities as a test of ionization theory.
- VIII. OBSERVATIONAL MATERIAL FOR THE TEST OF IONIZATION THEORY 116
- Measurement of line intensity.
 - Method of standardization.
 - Summary of results.
 - Consistency of results.
- IX. THE IONIZATION TEMPERATURE SCALE 133
- Consistency of the preliminary scale.
 - Effect of pressure.
 - Levels of origin of ultimate and subordinate lines.
 - Influence of relative abundance.
 - Method of determining effective partial pressure.
 - The corrected temperature scale.
- X. EFFECTS OF ABSOLUTE MAGNITUDE UPON THE SPECTRUM . . 140
- Influence of surface gravity on ionization.
 - Influence of pressure.
 - Influence of temperature gradient.
 - Comparison of predicted and observed effects.
 - Abnormal behavior of enhanced lines of alkaline earths.

PART III

ADDITIONAL DEDUCTIONS FROM IONIZATION THEORY

- XI. THE ASTROPHYSICAL EVALUATION OF PHYSICAL CONSTANTS . . . 155
 Spectroscopic constants (Plaskett).
 Critical potentials (Payne).
 Duration of atomic states (Milne).
- XII. SPECIAL PROBLEMS IN STELLAR ATMOSPHERES 161
 Class O stars.
 Class A stars.
 The Balmer lines.
 Classification of A stars.
 Silicon and Strontium stars.
 Peculiar Class A stars.
 c-stars.
- XIII. THE RELATIVE ABUNDANCE OF THE ELEMENTS 177
 Terrestrial data.
 Astrophysical data.
 Uniformity of composition of stellar atmospheres.
 Marginal appearance.
 Comparison of stellar and terrestrial estimates.
- XIV. THE MEANING OF STELLAR CLASSIFICATION 190
 Principles of classification.
 Object of the Draper Classification.
 Method of classifying.
 Finer Subdivisions of the Draper Classes.
 Implications of the Draper system.
 Homogeneity of the classes.
 Spectral differences between giants and dwarfs.
- XV. ON THE FUTURE OF THE PROBLEM 199

APPENDICES

- I. INDEX TO DEFINITIONS 203
 II. SERIES RELATIONS IN LINE SPECTRA 203
 III. LIST OF STARS USED IN CHAPTER VIII 205
 IV. INTENSITY CHANGES OF LINES WITH UNKNOWN SERIES RELATIONS 207
 V. MATERIAL ON A STARS, QUOTED IN CHAPTER XII 208
- SUBJECT INDEX 211
 NAME INDEX 214

PART I
THE PHYSICAL GROUNDWORK

CHAPTER I

THE LABORATORY BASIS OF ASTROPHYSICS

THE application of physics in the domain of astronomy constitutes a line of investigation that seems to possess almost unbounded possibilities. In the stars we examine matter in quantities and under conditions unattainable in the laboratory. The increase in scope is counterbalanced, however, by a serious limitation — the stars are not accessible to experiment, only to observation, and there is no very direct way to establish the validity of laws, deduced in the laboratory, when they are extrapolated to stellar conditions.

The verification of physical laws is not, however, the primary object of the application of physics to the stars. The astrophysicist is generally obliged to *assume* their validity in applying them to stellar conditions. Ultimately it may be that the consistency of the findings in different branches of astrophysics will form a basis for a more general verification of physical laws than can be attained in the laboratory; but at present, terrestrial physics must be the groundwork of the study of stellar conditions. Hence it is necessary for the astrophysicist to have ready for application the latest data in every relevant branch of physical science, realizing which parts of modern physical theory are still in a tentative stage, and exercising due caution in applying these to cosmical problems.

The recent advance of astrophysics has been greatly assisted by the development, during the last decade, of atomic and radiation theory. The claim that it would have been possible to predict the existence, masses, temperatures, and luminosities of the stars from the laws of radiation, without recourse to stellar observations, represents the triumph of the theory of radiation. It is equally true that the main features of the spectra of the stars could be predicted from a knowledge of atomic structure and the

origin of spectra. The theory of radiation has permitted an analysis of the central conditions of stars, while atomic theory enables us to analyze the only portion of the star that can be directly observed — the exceedingly tenuous atmosphere.

The present book is concerned with the second of these two problems, the analysis of the superficial layers, and it approaches the subject of the physical chemistry of stellar atmospheres by treating terrestrial physics as the basis of cosmical physics. From a brief working summary of useful physical data (Chapter I) and a synopsis of the conditions under which the application is to be made (Chapters II and III), we shall pass to an analysis of stellar atmospheres by means of modern spectrum theory. The standpoint adopted is primarily observational, and new data obtained by the writer in the course of the investigation will be presented as part of the discussion.

The first chapter contains a synopsis of the chief data which bear on atomic structure — the nuclear properties, and the disposition of the electrons around the nucleus. The origin of line spectra is discussed, and the ionization potentials corresponding to different atoms are tabulated. Lastly a brief summary is made of the effect of external conditions, such as temperature, pressure, and magnetic or electric fields, upon a line spectrum.

ATOMIC PROPERTIES ASSOCIATED WITH THE NUCLEUS

The properties determined by the atomic nucleus are the mass, and the isotopic and radioactive properties. The astrophysical study of these factors is as yet in an elementary stage, but it seems that all three have a bearing on the frequency of atomic species, and that future theory may also relate them to the problem of the source and fate of stellar energy. Moreover, up to the present no general formulation of the theory of the formation and stability of the elements has been possible, and it is well to keep in mind the data which are apparently most relevant to the problem — the observational facts relating to the nucleus. Probably the study of the nucleus involves the most fundamen-

tal of all cosmical problems — a problem, moreover, which is largely in the hands of the laboratory physicist.

The chief nuclear data are summarized in Table I. Successive columns contain the atomic number, the element and its chemical symbol, the atomic weight¹ and the mass numbers of the known isotopes,² the percentage terrestrial abundance,³ expressed in atoms, and the recorded stellar occurrence. Presence in the stars is indicated by an asterisk, absence by a dash.

TABLE I

No.	Element		Atomic Weight	Isotopes	Percentage Terrestrial Abundance (Atoms)	Stellar Occurrence
1	Hydrogen	H	1.008	1.008	15.459	*
2	Helium	He	4.00	4	..	*
3	Lithium	Li	6.94	7, 6	0.0129	*
4	Beryllium	Be	9.01	9	0.0020	—
5	Boron	B	11.0	11, 10	0.0016	—
6	Carbon	C	12.005	12	0.2069	*
7	Nitrogen	N	14.01	14	0.0383	*
8	Oxygen	O	16.00	16	54.940	*
9	Fluorine	F	19.0	19	0.0282	—
10	Neon	Ne	20.2	20, 22, (21)	..	—
11	Sodium	Na	23.00	23	2.028	*
12	Magnesium	Mg	24.32	24, 25, 26	1.426	*
13	Aluminum	Al	27.1		4.946	*
14	Silicon	Si	28.3	28, 29, 30	16.235	*
15	Phosphorus	P	31.04	31	0.0818	—
16	Sulphur	S	32.06	32	0.0518	*
17	Chlorine	Cl	35.46	35, 37, (39)	0.1149	—
18	Argon	A	39.88	40, 36	..	—
19	Potassium	K	39.10	39, 41	1.088	*
20	Calcium	Ca	40.07	(40, 44)	1.503	*
21	Scandium	Sc	44.1	45	..	*
22	Titanium	Ti	48.1	48	0.2407	*
23	Vanadium	V	51.0	51	0.0133	*

¹ International Atomic Weights, 1917.

² Aston, *Isotopes*, 1922; *Phil. Mag.*, 47, 385, 1924; *Nature*, 113, 192, 856, 1924; *Ibid.*, 114, 273, 716, 1924. Products of radioactive disintegration are omitted.

³ Clarke and Washington, *Proc. N. Ac. Sci.*, 8, 108, 1922.

No.	Element		Atomic Weight	Isotopes	Percentage Terrestrial Abundance (Atoms)	Stellar Occurrence
24	Chromium	Cr	52.0	52	0.0213	*
25	Manganese	Mn	54.93	55	0.0351	*
26	Iron	Fe	55.84	54, 56	1.485	*
27	Cobalt	Co	58.97	59	0.0009	*
28	Nickel	Ni	58.68	58, 60	0.0091	*
29	Copper	Cu	63.57	63, 65	0.0028	*
30	Zinc	Zn	65.37	(64, 66, 68, 70)	0.0011	*
31	Gallium	Ga	69.9	69, 71	..	*
32	Germanium	Ge	72.5	74, 72, 70	..	-
33	Arsenic	As	74.96	75	..	-
34	Selenium	Se	79.2		..	-
35	Bromine	Br	79.92	79, 81	..	-
36	Krypton	Kr	82.92	84, 86, 82, 83, 80, 78	..	-
37	Rubidium	Rb	85.45	85, 87	..	*
38	Strontium	Sr	87.63	88, 86	0.0065	*
39	Yttrium	Y	88.7	89	0.0030 (with Ce)	*
40	Zirconium	Z	90.6	90, 92, 94	0.0095	*
41	Niobium	Nb	93.1		..	?
42	Molybdenum	Mo	96.0		..	*
43	..	..			..	..
44	Ruthenium	Ru	101.7		..	*
45	Rhodium	Rh	102.9		..	*
46	Palladium	Pd	106.7		..	*
47	Silver	Ag	107.88	107, 109	..	*
48	Cadmium	Cd	112.40	110, 111, 112, 113, 114, 116	..	*
49	Indium	In	114.8		..	-
50	Tin	Sn	118.7		..	?
51	Antimony	Sb	120.2		..	-
52	Tellurium	Te	127.5	126, 128, 130	..	-
53	Iodine	I	126.92	127	..	-
54	Xenon	Xe	130.2	129, 132, 131, 134, 136, (128, 130)	..	-
55	Caesium	Cs	132.81	133	..	*
56	Barium	Ba	137.37	138	0.0098	*
57	Lanthanum	La	139.0	139	..	*
58	Cerium	Ce	140.25	140, 142	0.0030 (with Y)	*
59	Praseodymium	Pr	140.9	141	..	-

No.	Element	Atomic Weight	Isotopes	Percentage Terrestrial Abundance (Atoms)	Stellar Occurrence	
60	Neodymium	Nd	144.3	142-150	..	-
61	..	..			..	..
62	Samarium	Sa	150.4		..	-
63	Europium	Eu	152.0		..	*
64	Gadolinium	Gd	157.3		..	-
65	Terbium	Tb	159.2		..	*
66	Dysprosium	Dy	162.5		..	-
67	Holmium	Ho	163.5		..	-
68	Erbium	Er	167.7		..	-
69	Thulium	Tm	168.5		..	-
70	Ytterbium	Yb	173.5		..	-
71	Lutecium	Lu	175.0		..	-
72	Hafnium	Hf			..	-
73	Tantalum	Ta	181.5		..	-
74	Tungsten	W	184.0		..	-
75	..	..			..	-
76	Osmium	Os	190.9		..	-
77	Iridium	Ir	193.1		..	-
78	Platinum	Pt	195.2		..	-
79	Gold	Au	197.2		..	-
80	Mercury	Hg	200.6	(197, 198, 199, 200) 202, 204	..	-
81	Thallium	Tl	204.0		..	-
82	Lead	Pb	207.2		0.0002	*
83	Bismuth	Bi	208.0		..	-
84	..	..			..	..
85	..	..			..	..
86	Radon	Rd	222.4		..	-
87	..	..			..	..
88	Radium	Ra	226.0		..	-
89	..	..			..	..
90	Thorium	Th	232.4		..	-
91	..	..			..	..
92	Uranium	U	238.2		..	-

1925HarMo...1.....P

ARRANGEMENT OF EXTRA-NUCLEAR ELECTRONS

Logically a description of the analysis of spectra should precede the discussion of electron arrangement, for our knowledge of the extra-nuclear electrons is very largely based on spectroscopic evidence. The established conceptions of atomic structure, however, are useful in classifying mentally the general outlines of the origin of line spectra, and therefore, for convenience of reference, Bohr's table⁴ of the arrangement of extra-nuclear electrons is here prefixed to our brief discussion of spectroscopic data. The chemical elements are given in order of

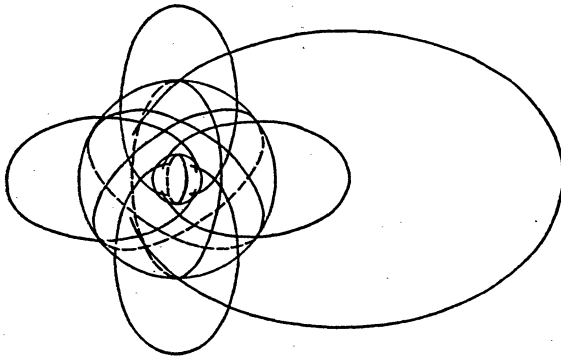


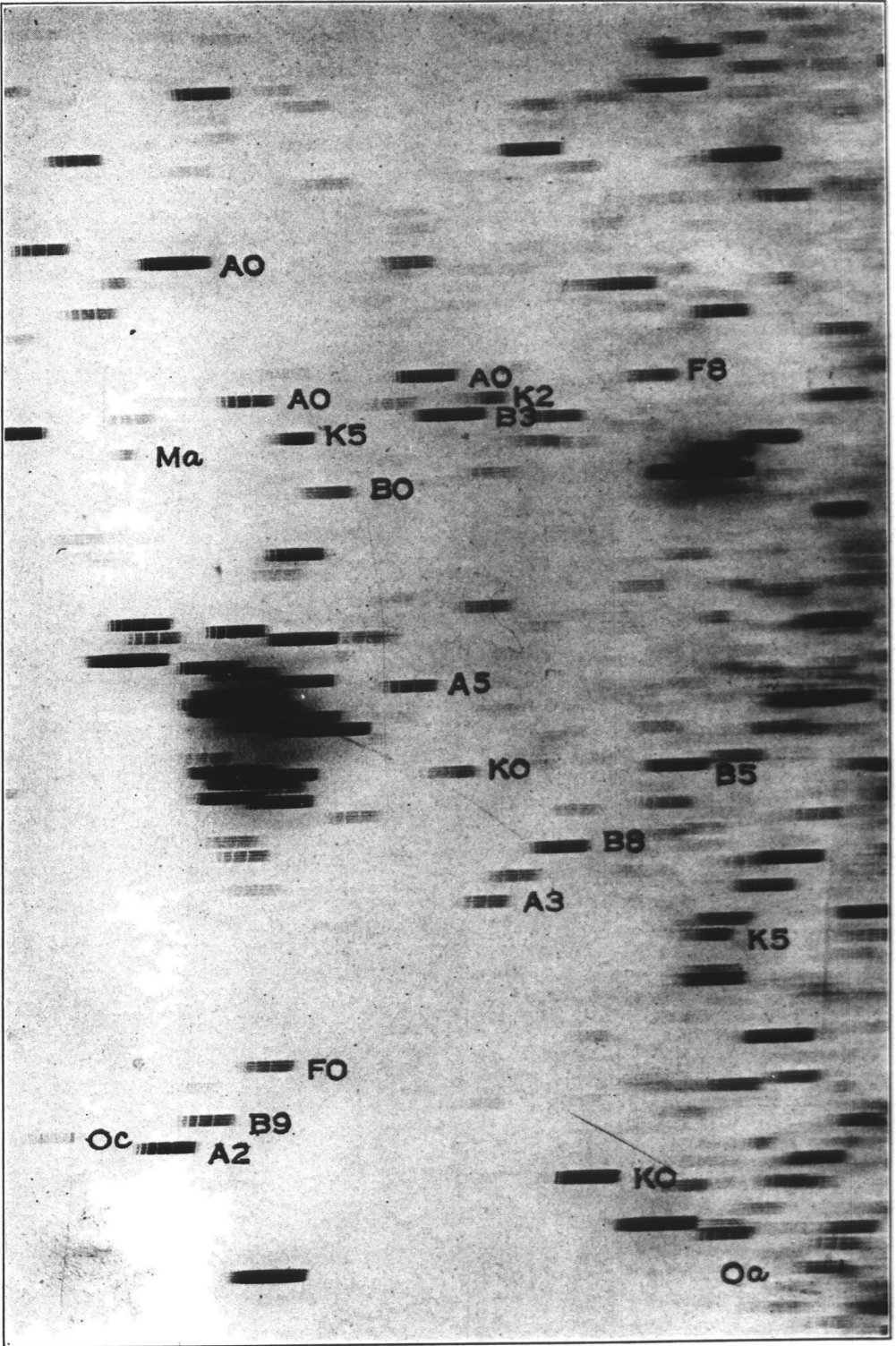
FIGURE I

Arrangement of electron orbits for the atom of neutral sodium. Orbits consisting partly of broken lines are circular orbits seen in perspective. The numbers and quantum relations of the orbits are as follows; inner shell, two 1_1 orbits; next shell, four 2_2 orbits and four 2_1 orbits; outer electron, one 3_1 orbit.

atomic number, and successive columns contain, for the atom in its normal state, the numbers of electrons in the various quantum orbits. In accordance with the notation of Bohr and Kramers,⁵ the first figure in the orbit-designation that stands at the head of a column denotes the total quantum number, which determines the length of the major axis of the corresponding orbit. The subscript is the so-called azimuthal quantum number, which determines the ellipticity of the orbit; the orbits with the smallest azimuthal quantum numbers are the most eccentric,

⁴ Bohr, *Naturwiss.*, 11, 619, 1923.

⁵ Sommerfeld, *Atombau und Spektrallinien*, 3d edition, 286, 1922.



- Landé 25
 Lee 71
 Lindblad 48, 57, 62, 169
 Lindemann 26
 Lockyer, J. N. 64, 70, 172, 173
 Lundmark 198
 Lunt 5, 85
 Luyten 67, 162, 170
 Lyman 18, 57, 58
- Maury 173
 McLennan 18, 63
 Meggers 13, 17, 72, 75, 82
 Menzel, 44, 66-68, 71, 74-76, 79-81, 85,
 109, 116, 133, 166, 181
 Merrill, G. P. 187
 Merrill, P. W. 54, 83
 Merton 25, 60, 62
 Mie 22
 Millikan 18
 Milne, 17, 22, 28, 36, 37, 44, 48, 50, 61,
 70, 93, 97, 106-110, 113, 133, 135, 140,
 156, 158, 166, 179
 Mitchell 58, 86
 Mohler 17
 Mulliken 61
- Newall 63
 Nicholson, J. W. 43
 Noyes 112
- Pannekoek 35, 140
 Paschen 14, 17, 156
 Payne 20, 38, 43, 58, 60, 68, 156, 163, 183
 Plaskett, H. H., 14, 30, 48, 51, 54, 59, 60,
 64, 65, 85, 156, 163, 184
 Plaskett, J. S. 60, 71, 162, 163, 171
 Pluvinel 62
 Ramage 81
 Rognley 17
 Rosenberg 29
 Rowland 127
 Ruark 17
 Rufus 62, 72
 Russell, 17, 26, 37, 39, 40, 44, 47, 52, 55,
 56, 59, 70, 79, 80, 110, 175, 178, 184, 203
- Saha 43, 85, 105, 113
 St. John 25, 38
 Sampson 30
 Saunders 38, 55, 203
 Scheiner 29
 Schwarzschild 51, 137, 160
 Seares 31
 Shane 62
 Shapley, 36, 40, 51, 62, 162, 168, 170, 185
 198
 Shaver 17
 Shrum 64
 Slipher 75
 Smyth 17, 19
 Sommerfeld 13, 17, 21, 23
 Sponer 17
 Stark 25
 Stewart 26, 37, 39, 40, 44, 47, 91, 110, 175
 Strutt 66
- Takamine 26
 Tate 17
 Thomas 18
 Turner 22
- Udden 17
 Urey 108
- Van Maanen 162
 Vegard 63
 Violle 60
 Von Zeipel 185
- Walters 13, 72, 77, 79
 Washington 5, 184, 185
 Webb 22
 Wien 22
 Wilsing 29, 48
 Wilson, E. B. 162
 Wilson, H. A. 112
 Wilson, H. H. 162
 Woltjer 113
 Wood 22, 42, 57
 Wright 43, 56, 57, 66, 163, 173
 Young 79, 117, 176, 192
 Zeemann 25