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OF NOVA HERCULIS, 1963.

The University of Michigan, Ph.D., 1964
Astronomy

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PHOTOELECTRIC SPECTROPHOTOMETRY OF NOVA HERCULIS, 1963

by
Stephen Paul Maran

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in the
University of Michigan
1964

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ACKNOWLEDGMENTS

I am deeply grateful to Professor Dean B. McLaughlin for his constant encouragement, for his valuable advice and critical discussions of all aspects of the present investigation, and for the communication of unpublished observations of Nova Herculis 1963.

I thank Professor William P. Bidelman for his encouragement and suggestions, particularly in regard to the subjects of interstellar reddening and the determination of distances to novae.

Appreciation is also expressed to Professor Orren C. Mohler for his encouragement and advice, for authorizing the extensive observing time that was necessary for this project, and for providing the funds required for the maintainance of the apparatus and the purchase of new equipment.

Associate Professor Herschel Weil's suggestions in regard to the preparation of this manuscript have considerably improved the clarity of presentation; they are gratefully acknowledged.

Thanks are due to Dr. Alastair G.W. Cameron, Senior Research Associate at the Goddard Institute for Space Studies, for helpful discussions of many astrophysical topics. His comments and ideas have greatly broadened my scientific horizons.

Gratitude is expressed to Professor Lawrence H. Aller of the University of California, Los Angeles and Assistant Professors Guenther H.E. Elste, John M. Malville and Richard G. Teske of the University of Michigan for helpful discussions concerned with the physical interpretation of the observations of Nova Herculis 1963. I have also benefitted from discussions on various topics related to this investigation with Drs. Robert C. Bless (University of Wisconsin), Aden B. Meinel (University of Arizona), É.R. Mustel (Astronomical Council, Academy of Sciences, U.S.S.R.), John B. Oke (Mt. Wilson and Palomar Observatories), Waltraut C. Seitter (Bonn University Observatory), and Merle F. Walker (Lick Observatory).

Among my present and former student colleagues at the University of Michigan, I am indebted to Dr. Peter B. Boyce, Mr. William A. Dent and Mrs. Hélène R. Dickel for helpful discussions, to Messrs. Hugh D. Aller and Thomas R. Gurski for assistance in taking some of the observations, and to Mr. Michael E. Dewey for making an English translation of Dr. W.C. Seitter's study of Nova Herculis 1963 (Veröff. Bonn No. 67). Further, I am grateful to a large number of students and staff members of the Department of Astronomy, University of Michigan, for providing transportation between Ann Arbor and the Portage Lake Observatory. Especially to be thanked in this regard are Miss Amy M. Fee and Messrs. John R. Dickel, Jerry R. Ehman and Robert G. Knighton.

I express particular thanks to Mr. Harvey P. Davidson, representative of the Underwood Corporation for southeastern Michigan, for generously supplying the electric typewriter with which this thesis was prepared and the Olivetti Tetractus printing calculator on which the computations were performed.

The manuscript was ably typed by Miss Christine Paraschos.

Finally, I thank my wife Joyce for preparing the illustrations and for her great patience.

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CHAPTER I

INTRODUCTION

Nova Herculis 1963

A fourth-magnitude nova was discovered at 11:45 U.T. on February 6, 1963 by L.C. Peltier (1963a) of Delphos, Ohio. The position of the star was very close to the border of the constellations Lyra and Hercules. Therefore a name could not be assigned to the nova until a definitive position measurement was available. Such a measurement was provided by Newsom and Chester (1963), who used a plate taken in 1920 with the 16-inch Metcalf refractor of the Harvard College Observatory. Their result was

$$\text{(equinox 1950.0)} \quad \alpha = 18^h12^m46^s.4$$
$$\delta = +41°50'21'' .$$

This position is in good agreement with independent measurements made on post-discovery plates by Barlier (1963), Pipping (1963) and Arend (1963), and it shows that the nova is located in Hercules. A position reported by Luyten (1963), based on a plate taken in 1951 with the 48-inch Schmidt telescope at Mt. Palomar Observatory, differs from that given above by 6' in declination and 2^s in right ascension; presumably it is based on a misidentification of the pre-outburst nova. It should be pointed out that although Peltier made the first observation of Nova Herculis 1963, he waited for two days in order to confirm his find by repeated observations before

announcing the discovery. During this period, an independent discovery was made by E. Dahlgren (1963) of Vikmanshyttan, Sweden. The credit for first advising astronomers of the occurrence of the nova must go to Dahlgren.

The nova was verified on the morning of February 8th by Engver (1963), who took objective-prism spectra at Lund Observatory. On the next morning McLaughlin (1963a) and his students, A.P. and C.R. Cowley, obtained five spectrograms of the nova with the 37-inch reflector at the Observatory of the University of Michigan. A strong resemblance between the spectrum of the present nova and that of Nova DN Geminorum 1912 was already evident on these plates, and in fact the subsequent spectral development of Nova Herculis 1963 has shown a considerable resemblance to that of DN Geminorum (McLaughlin 1963b). Both McLaughlin (1963a) and Larsson-Leander (1963), the latter using Engver's plates, concluded from the appearance of the spectrum that maximum light had occurred before the nova was discovered. This conclusion was verified by examination of pre-discovery photographs taken with Baker-Nunn cameras at the Mitaka, Japan and San Fernando, Spain satellite tracking stations of the Smithsonian Astrophysical Observatory. The approximate magnitudes that were determined from these films (Liller 1963; Anonymous 1963) are given in Table 1.

Table 1

Magnitude Estimates from Baker-Nunn Films

Date	U.T.	m	Station
1963			
January 26	18^h07^m	8.	Mitaka
January 30	17^h39^m	3.	Mitaka
February 3	03^h59^m	4.	San Fernando
February 3	18^h23^m	4.	Mitaka

The published early post-discovery magnitude estimates of Nova Herculis 1963 are summarized in Table 2.

Table 2

Apparent Magnitude of Nova Herculis 1963

February 6 - 9, 1963

Date	U.T.	m_v	Observer
1963			
February 6	11^h45^m	4.0	Peltier (1963b)
February 6	19^h20^m	3.9	Dahlgren (1963)
February 8	01^h50^m	3.8*	Helt and Glydenkerne (1963)
February 8	11^h00^m	4.1	Peltier (1963b)
February 9	09^h30^m	4.0	Milon (1963)
February 9	10^h00^m	3.9	Maran (1963)
February 9	----	4.09 ± 0.03	Gaposchkin (1963)
February 9	----	4.2†	Steinon (1963)

* Photoelectric measurement. † m_{pg} is given.

The visual light curve for the first two hundred days after the outburst occurred, prepared by the American Association of Variable Star Observers, is given in Figure 1. Breckinridge (1964) obtained six-color observations of the nova on eight nights between May 15 and August 3, 1963. For a 30 minute interval on June 1, 1963, he determined that the upper limit to the amplitude of rapid fluctuations in the brightness measured with the ultraviolet, blue, green and red filters was $0^{m}.01$. Clarke (1964) obtained photoelectric measurements, presumably without a filter, on eleven nights between February 15 and March 4, 1963, and also on March 19, 1963. He used a double beam photoelectric polarimeter with the 15-inch astrographic refractor of the Wilfred Hall Observatory. Clarke found that the degree of linear polarization in the nova was 0.6 ± 0.2 per cent and that it remained constant from night to night. He concluded that the polarization was probably due to the interstellar medium. The pre-outburst photographic magnitude of the nova was 14.2 ± 0.1, according to Stephenson and Herr (1963), who studied Lick and Palomar survey prints. M.F. Walker (private communication) has examined a pre-discovery plate on which several exposures of the region of the nova were obtained at intervals of two hours. He finds no evidence for light variations in the pre-nova on this plate.

Stephenson and Herr (1963) describe the pre-outburst spectrum of Nova Herculis 1963, as recorded on an objective-

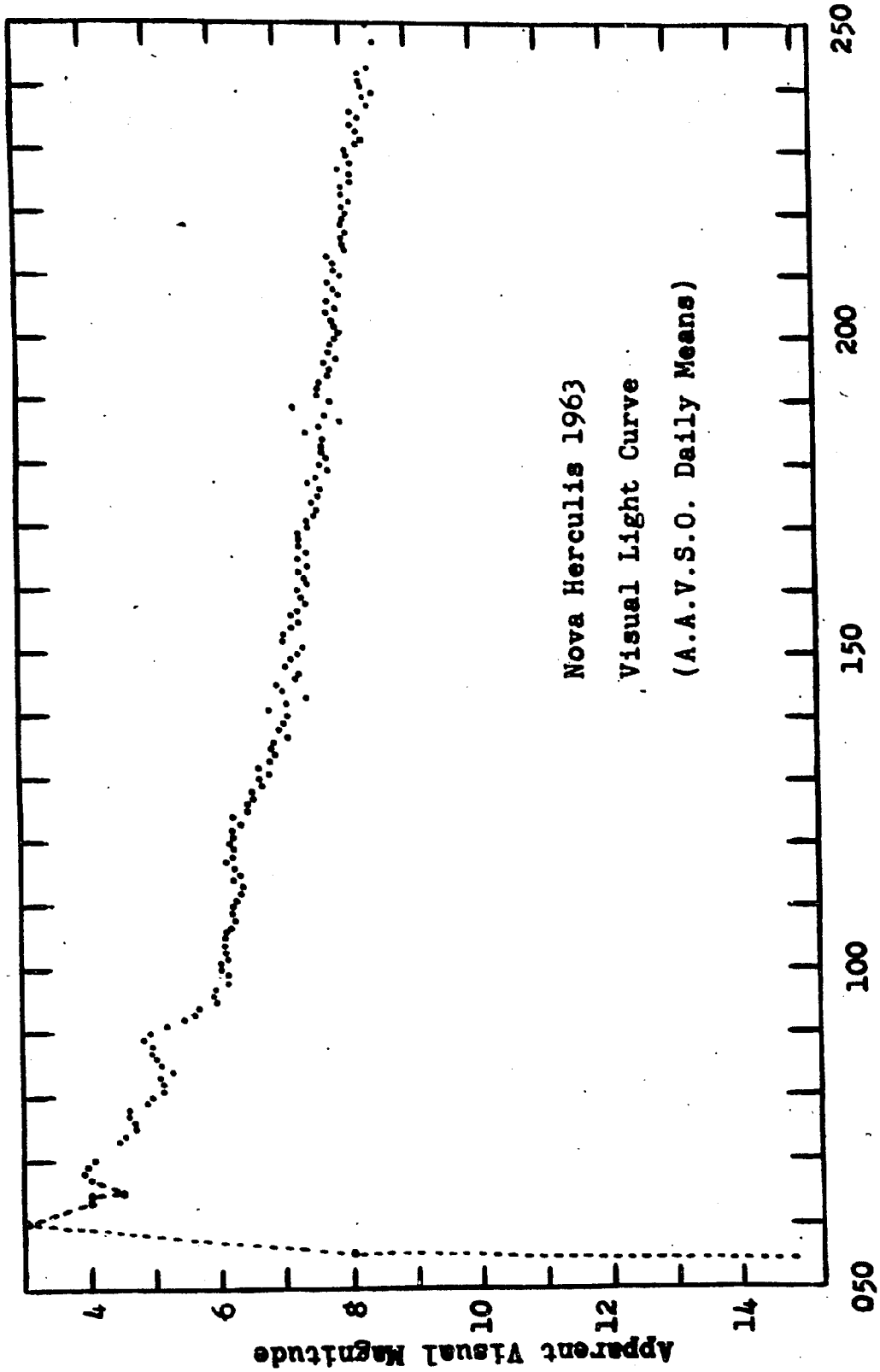

Nova Herculis 1963
Visual Light Curve
(A.A.V.S.O. Daily Means)
Apparent Visual Magnitude
4
6
8
10
12
14
050
100
150
200
250
Julian Day - 2,438,000

Figure 1

prism plate that was taken on June 16, 1961 with the Schmidt telescope of the Warner and Swasey Observatory. Although the spectrum is underexposed, it is of considerable interest, since pre-outburst nova spectra have been reported for only one other nova (Cannon 1920). The continuum in the range 3300 Å to 4800 Å resembles that of a "little-reddened O or very early B star"; further, no evidence for hydrogen lines as strong as those of an A type dwarf is found by Stephenson and Herr. It is interesting to compare this result with that of Miss Cannon (1920), who considered that the pre-outburst spectrum of Nova V603 Aquilae 1918 "was probably of some division of Class A."

Spectroscopic investigations of Nova Herculis 1963 have been reported by Ahlmark and Clemert (1964), Andrillat and Bloch (1963), Baschek (1964), Batten, Richardson and Wright (1963), Bloch and Chalonge (1963), McLaughlin (1963a and b), Orlov and Rodriguez (1964), and Seitter (1964).

The similarity of the spectral behavior of the present nova to that of Nova DN Geminorum 1912 was mentioned above. However, Nova Herculis 1963 did show at least one major peculiarity, namely fluctuations in the intensities and positions of the Orion absorption lines that were quite large, considering the small associated light variations (McLaughlin 1963b). The average velocity of the Principal system during the interval from February 9 to April 20 was about 1000 km/sec (McLaughlin 1963), as measured on slit spectrograms. Measure-

ments of the Principal velocity on objective prism plates are systematically different: during the interval from February 18 to March 25, 1963, Ahlmark and Clemert (1964) found a mean value of 1160 km/sec, and Miss Seitter (1963) found a mean value of -1119 km/sec.*

Unsuccessful attempts to detect radio emission from Nova Herculis 1963 were made by Haddock, Howard, Malville and Seling (1963) and by Hogg (1963). Their results are summarized in Table 3.

Table 3

Upper Limits to Radio Emission from Nova Herculis 1963

Frequency	Flux Density	Observer
Mc/s	$Wm^{-2}\ (c/s)^{-1}$	
750	3×10^{-27}	Hogg (1963)
1400	2×10^{-27}	Hogg (1963)
8000	3×10^{-27}	Haddock et.al. (1963)

The observations by Haddock et al. were taken on February 9, 12, 14 and 16, 1963; Hogg observed on six days during the interval from February 9 to March 22, 1963.

*For the violet components of the Balmer lines.

Recent Work on Novae

Although titled "The Spectra of Novae," a recent review article by McLaughlin (1960) summarizes nearly all that was known about novae at the time that it was written (the original draft was completed in mid-1958). Since that time, however, several notable contributions have been published; they are summarized below.

Perhaps the most significant recent development in the study of novae has occurred as a result of the examination, by spectroscopic and photometric techniques, of ten old novae and recurrent novae. The 100-inch and 200-inch telescopes at Mount Wilson and Palomar Observatories were used in this work by Walker (1954 and 1962) and Kraft (1958, 1961 and 1964). They found that at least six and probably seven of the ten stars are members of binary systems. The observational data on these binaries are in accord with the following hypothesis, which was advanced by Crawford and Kraft (1956) in a discussion of AE Aquarii, an SS Cygni star: each binary consists of a red component that fills a lobe of the inner zero-velocity surface defined by the restricted three-body problem and a blue component of lesser size; the luminosity of the blue star is maintained perhaps by heating due to the accretion of matter that escapes from the red star and passes through the inner Lagrangian point, forming a ring or shell around the blue component. Some astronomers now believe that all novae are binary stars. This subject is discussed in a series of papers called "Binary Stars Among Cataclysmic Variables" (Kraft 1962 and

1964; Kraft, Mathews, and Greenstein 1962; Mumford 1964).

Hazlehurst (1962) discussed the problem of the propagation of a shock wave through the interior of a nova after the release (by an unspecified process) of an arbitrary amount of energy at the center of the star. He found that only about one per cent of the initial energy goes into the escape of the nova shell. Ten per cent of the energy is deposited in the outer layers of the star, which then form an expanded isothermal atmosphere with a temperature of about 10^6 °K* and a scale height of about 10^3 km.* The bulk of the energy is retained by the star and is not involved in the nova outburst. Hazlehurst suggested that this energy may be stored in the form of rapid oscillations, such as those observed in Nova DQ Herculis 1934 by Walker (1956). The ejection of the shell takes place in a time of the order of minutes. The problem of the evolution of the extended atmosphere is not solved, but presumably the star eventually returns to its original configuration.

A valuable contribution to the interpretation of observations of novae has been made in the form of a series of five papers, called "The Nova Outburst," by Pottasch (1959 a, b, c, and d) and Jefferies and Pottasch (1959). The post-outburst nova phenomena are interpreted in terms of a simple model based on the assumption that most of the

---

*For a star of one solar mass with radius $R_s = 0.1\ R_\odot$.

ejected matter is confined to a single thin shell. This model is discussed in some detail in Chapter III. The transfer of radiation through the expanding shell during the first few days while the shell is still opaque to visible radiation is analyzed and it is found that the theoretical luminosity and temperature of the shell, as functions of time, are in accord with the observational data. Strömgren's (1939 and 1948) theory for the ionization of a hydrogen cloud by an exciting star is extended, taking into account the scattered ionizing quanta as well as the direct flux from the star. The electron density and temperature of the ionized shell are determined from the intensity of Hα and the ratio of the intensities of the strong [O III] lines,

$$\mathcal{R}(O^{++}) = \frac{I(4363)}{I(4959 + 5007)} \; ;$$

the effects of collisional processes are included. Other physical parameters of novae are also determined, by methods similar to those described in Chapter III.

A major advance in the determination of accurate spectral intensity distributions for novae has been the application of the technique of photoelectric spectrophotometry to this problem. Meinel (1963) published the first investigation of this type. He studied Nova Herculis 1960 in the spectral range from 3450 Å to 6570 Å, using a 40 Å

slit. Meinel's results on the emission lines were presented chiefly in terms of intensities relative to the continuum. However, the ratios of the hydrogen lines to each other, i.e.: the Balmer decrement, were also given. The present study constitutes a first determination of absolute emission-line intensities in a nova by means of photoelectric spectrophotometry. Both Nova Herculis 1960 and Nova Herculis 1963 have been observed by this method at the Washburn Observatory (Bless, private communication); however the results are not yet available.

A few other recent papers should be mentioned:

Mustel (1963) describes a method for the determination of the electron density from observations of Balmer absorption lines made near maximum light. Bashkin and Meinel (1964) have produced a simulated nova emission spectrum in the laboratory, using a van de Graaff accelerator as a source of fast particles. Mme. Iwanowska and Burnicki (1962) find that when novae are grouped according to absolute magnitude at maximum light, the brighter stars are more concentrated toward the galactic plane (or the galactic center). Schmidt-Kaler (1962) has found an improved value of the mean absolute magnitude of novae at minimum light, namely $M_{pg} = +4.3$.

CHAPTER II

OBSERVATIONS

Instrumentation

All of the observations taken in this program were made with the Francis C. McMath Memorial 24-inch Reflector (McMath 1941) at its new location at the Portage Lake Observatory. The photoelectric spectrophotometer employed was constructed by R.G. Tull (1963). P.B. Boyce (1963) modified the telescope drive system, the spectrophotometer, and the associated electronics. A tri-alkali EMI 9558 QA photomultiplier tube and General Radio 1230A D.C. amplifier were employed in the present investigation. The data were taken almost exclusively in the second order of the grating. Boyce (1963) describes the manner in which the amplifier gains, time constants, slit widths and wavelength meters have been calibrated. The procedure for determination of the wavelength-dependent absolute sensitivity of the apparatus is discussed in the section on Reduction of Observational Data of this chapter. The various scanning rates of the spectrophotometer, as determined by measurements of the separations of points of known wavelength on the observational records, were generally found to be equal within $\pm$ 1 per cent to the values quoted by Tull (1963), that is 270, 90 and 30 Å/min, but on four very cold nights the measured rates (Table 4) were slower.

Observational Procedure

Nova Herculis 1963 is located roughly 5° northwest

of the bright star alpha Lyrae (Vega), whose absolute energy distribution has been determined photoelectrically by several astronomers. Therefore, Vega was adopted as the standard star for this investigation and was observed in order to determine the sensitivity of the telescope-spectrophotometer system as a function of wavelength. The observations of Vega were also used to derive atmospheric extinction laws, and for this purpose were supplemented on a few nights by observations of alpha Cygni (Deneb). Details concerning the determination of the extinction and sensitivity laws, as well as the adopted energy distributions for Vega and Deneb and the pertinent literature references, are given in the section on Reduction of Observational Data of this chapter.

The observations of Vega and Deneb consisted of measurements of the intensity of each of nine 10.5 Å bands in the range 3860 - 6670 Å. These data were not obtained by making scans of the spectrum. Instead, the spectrophotometer was used as a monochromator, and the average deflection over about 30 seconds was measured in each of the nine 10.5 Å bands. This procedure has the advantage that it is possible to eliminate the effect of short-period fluctuations due to both atmospheric "seeing" and noise in the photomultiplier tube. For a bright star such as Vega, the latter effect is negligible except at the two longest wavelengths of observation, 6050 Å and 6670 Å, where the sensitivity of the apparatus

is very low. The wavelengths of all nine bands are listed in Table 5. Typical records of measurements on Vega in two bands are presented in Figure 2; note that the dark reading is a straight horizontal line, which shows that the noise evident in the records taken on the star is almost entirely due to the "seeing" near the zenith, where Vega was located at the time this observation was made. Ideally, our procedure on each observing night was to make at least two consecutive sets of observations of each of the nine 10.5 Å bands in the spectrum of the standard star before each observation of the nova, and to make at least two more sets of standard star measurements thereafter. In practice, however, variable atmospheric conditions often limited the number of observations that could be made, and in fact no useful standard star data were obtained on the first two observing nights. The actual number of calibration observations for each night is given in Table 4.

Observations of Nova Herculis 1963 were obtained on 22 nights, over an interval of 227 days, during which time the visual magnitude declined by about $4^{m}.5$ (G. Comello, private communication). The first observation was made on the morning of February 12, 1963 (J.D. 2,438,073) when the apparent magnitude was already about $1^{m}.5$ fainter than the poorly determined maximum (Figure 1). The observations consisted of photoelectric scans of selected regions of the spectrum between 3800 and 6800 Å. However, only the range 3860 - 6670 Å was calibrated, as the observations of

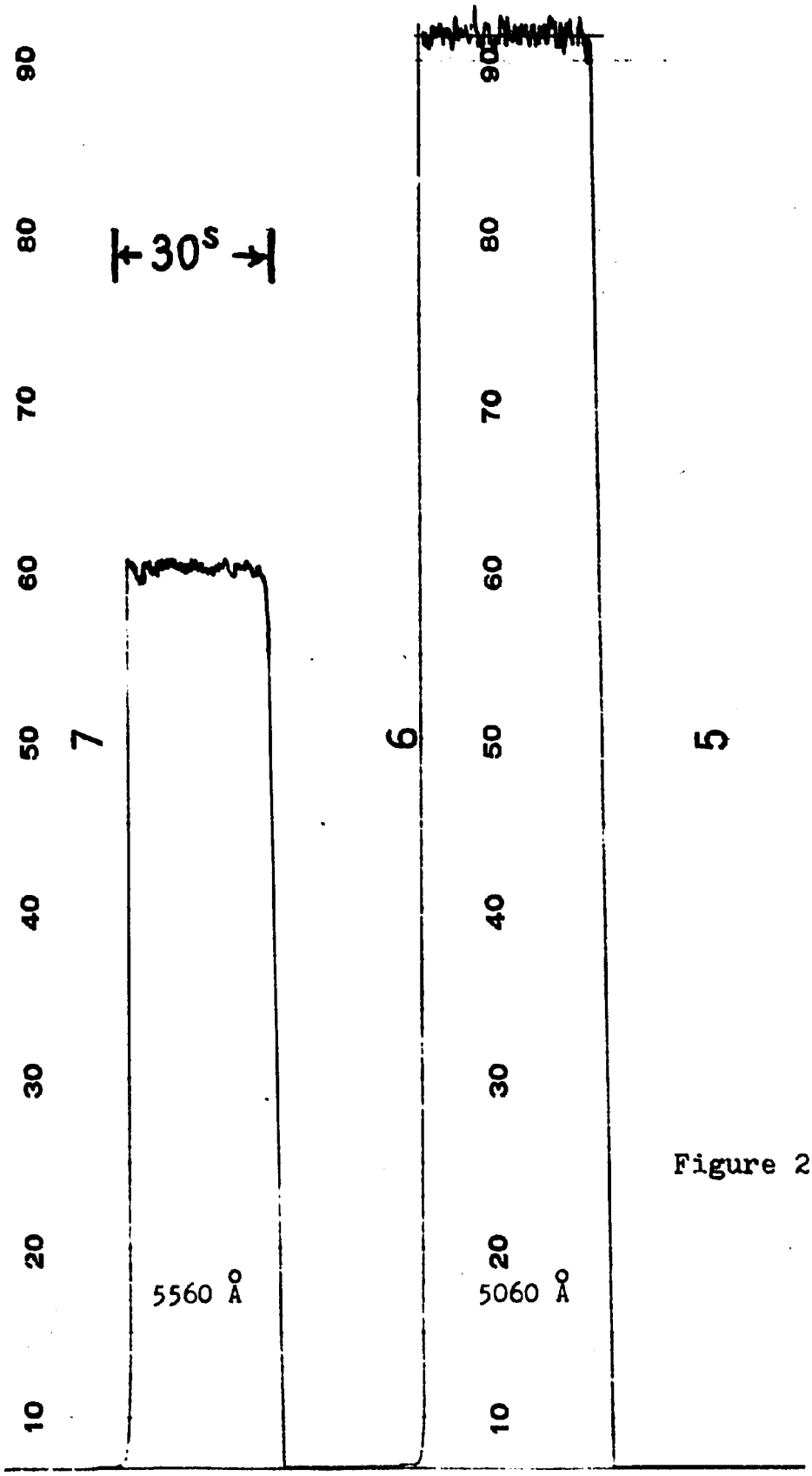


Figure 2

Monochromatic Observations

of alpha Lyrae

Vega were limited to this interval. Several settings of the exit slit width, which determines the bandpass of the spectrum that is admitted to the photocathode, were tried on the first few observing nights. Thereafter, a setting of 10.5 Å, which provided a good compromise between spectral purity and signal-to-noise ratio, generally was used, until a wider slit was required because some important emission lines had become too weak to measure with the 10.5 Å slit. A slit width of 21.4 Å was used primarily thereafter in the appropriate regions of the spectrum. Observations of the same spectral regions with both of these slit widths were made on a few nights, in order to determine whether the emission line intensities thus measured were in the expected ratio

$$\frac{I\ (10.5\ \text{Å slit})}{I\ (21.4\ \text{Å slit})} = 0.491 \quad .$$

No significant deviations from this ratio were found, which indicates that the effect of differences in the blending of adjacent emission features was small compared to other uncertainties in the measurements. Table 4 lists the spectral scans of Nova Herculis 1963 obtained in the present investigation. From left to right, the table lists the dates of observation, the serial numbers of the scans, the exit slit widths employed, the time constant of the R-C network through which the signal from the amplifier was passed before being displayed on the Brown

Table 4

Journal of Observations

Date	Scan #	Slit Width	Time Constant	Scan Rate	Range	Stds.
(1963)		(Å)	(sec.)	(Å/min)	(Å)	
Feb. 11-12	542 A	21.4	1.0	205	6800-6350	-----
	542 B	21.4	1.0	225	6300-6800	
	544 A	21.4	1.0	225	6750-6350	
	544 B	21.4	1.0	225	6400-6800	
	544 C	21.4	1.0	225	5300-4600	
	544 D	21.4	1.0	230	4600-5300	
	544 E	21.4	1.0	225	4500-3900	
	544 F	21.4	1.0	230	3900-4500	
	544 G	21.4	1.0	235	4500-6800	
Feb. 14-15	545 A	21.4	1.0	210	5800-4500	-----
	545 B	21.4	1.0	225	3800-4500	
	545 C	21.4	1.0	215	4500-4000	

Table 4 (continued)

Date	Scan #	Slit Width	Time Constant	Scan Rate	Range	Stds.
Feb. 14-15,	545 D	21.4	1.0	220	3800-4500	
continued	545 E	21.4	0.5	210	4500-4000	
	545 F	21.4	0.5	225	3800-4200	
Feb. 25-26	548 A	10.5	0.25	220	6800-6200	2V
	548 B	10.5	0.25	215	6200-6800	
	548 C	10.5	0.25	215	5800-4500	
	548 D	10.5	0.25	225	5800-4500	
	548 E	10.5	0.25	210	4500-3800	
	548 F	10.5	0.25	210	4500-3800	
March 13-14	559 A	10.5	0.25	245	4500-5800	4V
	559 B	10.5	0.25	240	5800-6800	
	559 C	10.5	0.25	245	6800-5800	
	559 D	10.5	0.25	240	5800-4500	
	559 E	10.5	0.25	240	4500-3800	
	559 F	10.5	0.25	245	3800-4500	

Table 4 (continued)

Date	Scan #	Slit Width	Time Constant	Scan Rate	Range	Stds.
April 4-5	565 A	10.5	0.25	270	4500-6000	4V
	565 B	10.5	0.25	270	5800-4500	
	565 C	10.5	0.25	270	5800-6800	
	565 D	10.5	0.25	270	6800-5800	
	565 E	10.5	0.25	270	4500-3800	
	565 F	10.5	0.25	270	3800-4500	
	565 G	10.5	0.25	270	4500-5800	
	567 A	15.9	0.5	270	5800-6800	
	567 B	15.9	0.5	270	6800-6000	
	567 C	15.9	0.5	270	6000-6800	
	567 D	15.9	0.25	270	6800-6000	
	567 E	15.9	0.25	270	6000-6800	
	567 F	15.9	0.25	270	5800-4500	
	567 G	15.9	0.25	270	4500-5950	
April 6-7	570 A	10.5	0.25	270	5800-4500	2V

Table 4 (continued)

Date	Scan #	Slit Width	Time Constant	Scan Rate	Range	Stds.
April 6-7	570 B	10.5	0.25	270	4500-5800	
continued	570 C	10.5	0.25	270	5800-6800	
	570 D	10.5	0.25	270	6800-5500	
April 15-16	574 A	10.5	0.5	270	4500-5900	1V
	574 B	10.5	0.5	270	5900-4500	
	574 C	10.5	0.5	270	6000-6800	
April 21-22	577 A	10.5	0.5	270	6800-6350	2V
	577 B	10.5	0.5	270	6350-6800	
	577 C	10.5	0.5	270	6800-6350	
	577 D	10.5	0.5	270	4500-5800	
	577 E	10.5	0.5	270	5800-4500	
	577 F	10.5	1.0	90	4500-5300	
April 24-25	581 A	10.5	1.0	90	5800-5600	2V
	581 B	10.5	1.0	90	5630-5200	
	581 C	10.5	1.0	90	5300-4500	

Table 4 (continued)

Date	Scan #	Slit Width	Time Constant	Scan Rate	Range	Stds.
April 26-27	584 A	10.5	1.0	90	4500-5300	4V
	584 B	10.5	1.0	90	5300-4500	
	584 C	10.5	1.0	90	6200-6800	
	584 D	10.5	1.0	90	6800-6400	
	586 A	10.5	1.0	90	3800-4500	
	586 B	10.5	1.0	90	4500-3800	
	586 C	10.5	1.0	90	4500-3970	
April 27-28	589 A	10.5	1.0	90	5230-4750	4V
	589 B	10.5	1.0	90	4730-5200	
	589 C	10.5	1.0	90	5200-4730	
	589 D	10.5	1.0	90	4750-5150	
	589 E	10.5	1.0	90	5150-4750	
	591 A	10.5	1.0	90	6800-6400	
	591 B	10.5	1.0	90	6400-6700	
	591 C	10.5	1.0	90	6700-6400	

Table 4 (continued)

Date	Scan #	Slit Width	Time Constant	Scan Rate	Range	Stds.
April 27-28	591 D	10.5	1.0	90	4500-3850	
continued	591 E	10.5	1.0	90	3820-4500	
	593 A	10.5	1.0	90	4500-5200	
	593 B	10.5	1.0	90	5200-4500	
	593 C	10.5	1.0	90	5800-5550	
	593 D	10.5	1.0	90	5550-5800	
	593 E	15.9	1.0	90	3600-3800	
	593 F	15.9	1.0	90	3800-3600	
May 1-2	600 A	10.5	1.0	90	6800-6450	4V
	600 B	10.5	1.0	90	6400-6650	
	600 C	10.5	1.0	90	6700-6400	
	600 D	10.5	1.0	90	5900-5550	
	600 E	10.5	1.0	90	5550-6050	
	600 F	10.5	1.0	90	6050-5550	
	600 G	10.5	1.0	90	5450-3800	

Table 4 (continued)

Date	Scan #	Slit Width	Time Constant	Scan Rate	Range	Stds.
May 1-2	600 H	10.5	1.0	90	3800-5550	
continued						
May 5-6	603 A	10.5	1.0	90	5300-4700	1V
	603 B	10.5	1.0	90	4700-5950	
May 20-21	608 A	10.5	1.0	90	5250-4500	4V
	608 B	10.5	1.0	90	4500-4800	
	608 C	10.5	1.0	90	4500-5250	
	608 D	10.5	1.0	90	6400-6700	
	608 E	10.5	1.0	90	6700-6400	
	608 F	10.5	1.0	90	4500-3916	
	608 G	10.5	1.0	90	3900-4500	
	608 H	10.5	1.0	90	5500-6020	
	608 I	10.5	1.0	90	6000-5500	
	608 J	31.8	2.5	90	6000-6650	
May 23-24	613 A	10.5	1.0	90	4500-5250	2V

Table 4 (continued)

Date	Scan #	Slit Width	Time Constant	Scan Rate	Range	Stds.
May 23-24	613 B	10.5	1.0	90	5250-4000	
continued	613 C	10.5	1.0	90	4000-4500	
	613 D	10.5	1.0	90	5500-6000	
	613 E	10.5	1.0	90	6000-5500	
	613 F	10.5	1.0	90	5500-6660	
	613 G	10.5	1.0	90	6660-5540	
May 30-31	617 A	10.5	1.0	90	3900-4500	4V
	617 B	10.5	1.0	90	4500-4000	
	617 C	21.4	2.5	90	4000-4500	
	617 D	21.4	2.5	90	4500-3900	
	617 E	10.5	1.0	90	4500-5150	
	617 F	10.5	1.0	90	5150-4550	
	617 G	10.5	1.0	90	6250-6650	
	617 H	10.5	1.0	90	6650-6450	
	617 I	10.5	1.0	90	6150-5580	
	617 J	10.5	1.0	90	5580-5980	

Table 4 (continued)

Date	Scan #	Slit Width	Time Constant	Scan Rate	Range	Stds.
May 30-31	617 K	21.4	2.5	90	5980-5580	
continued	617 L	21.4	2.5	90	5580-5980	
June 14-15	620 A	10.5	1.0	90	6650-6430	1V
	620 B	10.5	1.0	90	6430-6650	
	620 C	10.5	1.0	90	6650-6430	
	620 D	21.4	2.5	90	6430-6650	
	620 E	21.4	2.5	90	6650-6420	
June 17-18	625 A	10.5	1.0	90	3900-4500	2V,3D
	625 B	10.5	1.0	90	4500-3900	
	625 C	10.5	1.0	90	3900-4500	
	625 D	10.5	1.0	90	4500-3900	
	625 E	10.5	1.0	90	5250-4530	
	625 F	10.5	1.0	90	4530-5170	
	625 G	10.5	1.0	90	5390-6020	
	625 H	10.5	1.0	90	6020-5520	
	625 I	10.5	1.0	90	6200-6690	

Table 4 (continued)

Date	Scan #	Slit Width	Time Constant	Scan Rate	Range	Stds.
June 17-18	625 J	10.5	1.0	90	6690-6440	
continued	625 K	21.4	2.5	90	6440-6690	
	625 L	21.4	2.5	90	6690-5580	
June 20-21	631 A	10.5	1.0	90	6640-6440	1V,1D
	631 B	10.5	1.0	90	6440-6650	
	631 C	10.5	1.0	90	6650-6440	
	631 D	10.5	1.0	90	6440-6660	
	631 E	10.5	1.0	90	6660-6440	
	631 F	10.5	1.0	90	6440-6650	
	631 G	10.5	1.0	90	6250-4740	
	631 H	10.5	1.0	90	4740-5150	
July 2-3	633 A	10.5	1.0	90	6650-6450	1V,2D
	633 B	10.5	1.0	90	6450-6650	
	633 C	10.5	1.0	90	6650-6450	
	633 D	10.5	1.0	90	6450-6650	

Table 4 (continued)

Date	Scan #	Slit Width	Time Constant	Scan Rate	Range	Stds.
July 2-3	633 E	21.4	2.5	90	6650-6450	
continued	633 F	21.4	2.5	90	6450-6680	
	633 G	21.4	2.5	90	6650-6450	
	633 H	21.4	2.5	90	6450-6650	
	633 I	21.4	2.5	90	6652-6450	
	633 J	10.5	1.0	90	5250-4500	
	633 K	10.5	1.0	90	4500-5140	
	633 L	10.5	1.0	90	5140-4800	
	633 M	10.5	1.0	90	4800-5150	
	633 N	10.5	1.0	90	4500-4210	
	633 O	10.5	1.0	90	4210-4450	
Aug. 31 -	637 A	10.5	1.0	90	5250-4780	4V
Sept. 1	637 B	10.5	1.0	90	4770-5120	
	637 C	10.5	1.0	90	5120-4800	
	637 D	10.5	1.0	90	4500-4280	

Table 4 (continued)

Date	Scan #	Slit Width	Time Constant	Scan Rate	Range	Stds.
Aug. 31 -	637 E	10.5	1.0	90	4280-4500	
Sept. 1	637 F	10.5	1.0	90	6400-6650	
continued	637 G	21.4	2.5	90	6650-6430	
	637 H	21.4	2.5	90	6430-6680	
	637 I	21.4	2.5	90	6680-6400	
	637 J	21.4	2.5	90	6400-6680	
Sept. 26-27	647 A	10.5	1.0	90	4580-5120	3V
	647 B	10.5	1.0	90	5120-4800	
	647 C	10.5	1.0	90	4800-5110	
	647 D	21.4	2.5	90	5620-6030	
	647 E	21.4	2.5	90	6030-5680	
	647 F	21.4	2.5	90	5685-6000	
	647 G	21.4	2.5	90	6400-6640	
	647 H	21.4	2.5	90	6640-6440	
	647 I	21.4	2.5	30	6480-6630	
	647 J	42.9	2.5	90	6410-6670	

Recorder, the rate at which the spectrum was scanned, the approximate wavelength limits of the scan, and the number of standard star observations obtained. The last quantity is presented in the following way: the number of observations (n) of Vega is indicated by writing nV, and the number of observations of Deneb (m) is indicated by the term mD. Thus, the entry "2V" in the column headed "Stds." for Feb. 25-26, 1963 shows that two observations of Vega were obtained on that date, and the entry "1V,1D" for June 20-21 indicates that one observation each of Vega and of Deneb was taken. A "scan" is defined here as a record, obtained with the spectrophotometer in the scanning mode, which is preceded by either a dark reading or a reversal of the scanning direction and which is followed by either a dark reading or a reversal of the scanning direction. Thus, the first scan of each series is preceded by a dark reading, and every scan is immediately followed by either a dark reading or a reverse scan. A "standard star observation" is defined generally as a set of at least one record each of the intensities in the nine calibration bands, but on Aug. 31 - Sept. 1 and Sept. 26-27, ten bands were observed, and on April 21-22 and May 5-6, only seven and five bands, respectively, were observed. It is important to note that the number of standard star observations available for the determination of the extinction law for any night in the interval February 11-12 to July 2-3 is one greater than the number indicated in the last column of Table 4. This is

true because it was found in practice that a mean absolute instrumental sensitivity function was good to within a few per cent over this interval (here we anticipate a result presented in the next section), and thus we have available a zero-air-mass "observation" of Vega, since the energy distribution of Vega is known from the monochromatic magnitudes relative to the intensity at 5560 Å (Table 5) and the absolute calibration of that intensity (Code 1960).

The objective of the present investigation has been the determination of accurate absolute intensities for the strong emission lines. Due to the effects of variable atmospheric transparency, which sometimes cannot be detected until the data are reduced, and also to considerations of the signal-to-noise ratio, which decreased as the nova faded, it was felt desirable that the time available for observations of the nova should be devoted to making as many scans as possible of the strong lines. Therefore, the accuracy with which the weaker lines and the continuum have been measured is less than that of which the apparatus was capable because these measurements have been made with gains appropriate to the strong lines. Typical scans are shown in Figures 3-5.

Reduction of Observational Data

The intensity of a given emission line in the spectrum of Nova Herculis 1963 was determined in the following way: (1) A smooth curve was drawn to represent the assumed continuum on the scan. For records obtained in the interval

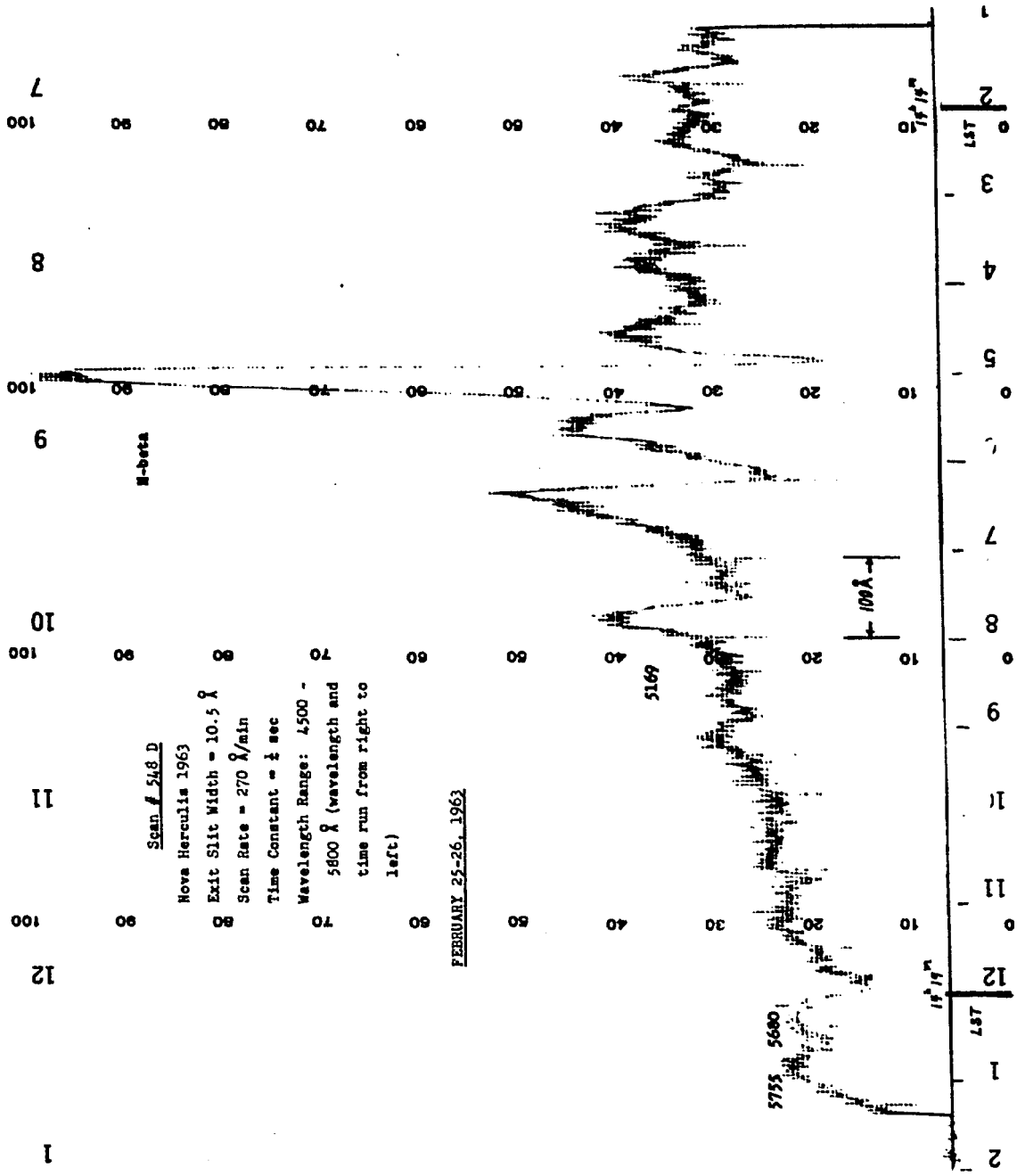

Scan # 548 D
Nova Herculis 1963
Exit Slit Width = 10.5 Å
Scan Rate = 270 Å/min
Time Constant = 1 sec
Wavelength Range: 4500 - 5800 Å (wavelength and time run from right to left)
FEBRUARY 25-26, 1963
H-beta
5169
5755
5680
100Å
LST
LST

Figure 3

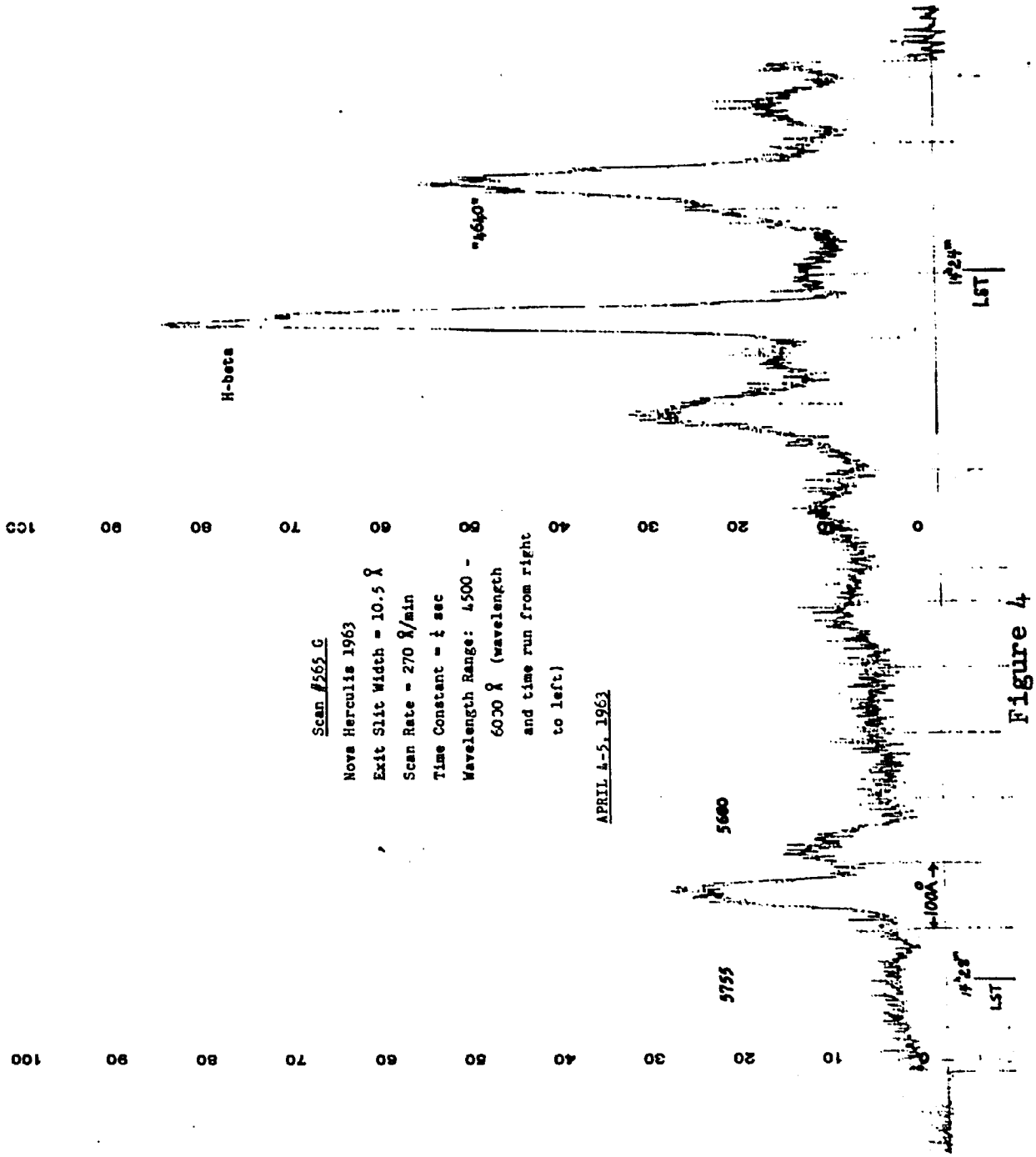

Scan #565 G
Nova Herculis 1963
Exit Slit Width = 10.5 Å
Scan Rate = 270 Å/min
Time Constant = 1 sec
Wavelength Range: 4500 - 6030 Å (wavelength and time run from right to left)
APRIL 4-5, 1962
H-beta
"4640"
5680
5755
~100Å
14h24m LST
14h28m LST
0
10
20
30
40
50
60
70
80
90
100

Figure 4

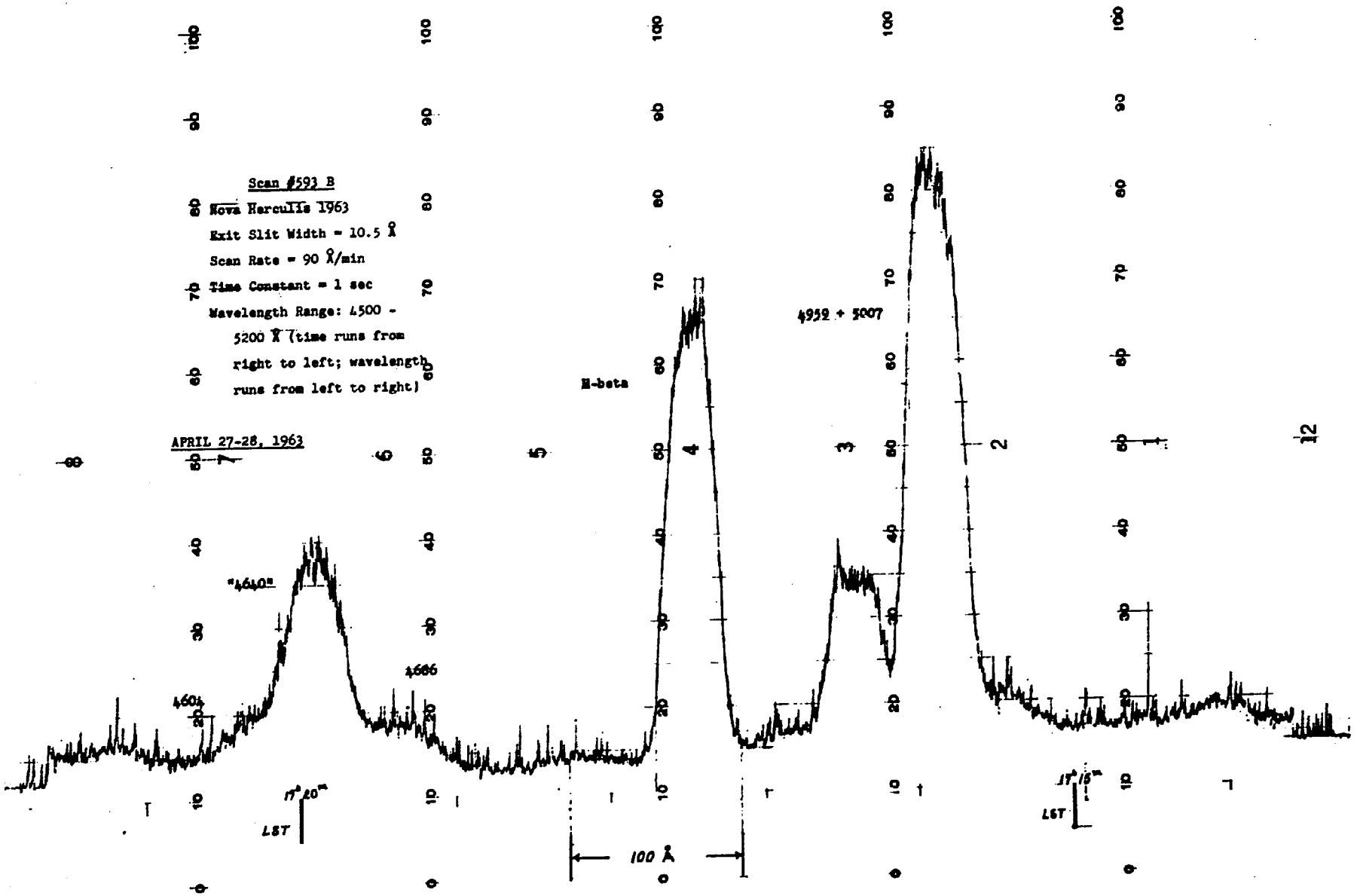

Scan #593 B
Nova Herculis 1963
Exit Slit Width = 10.5 Å
Scan Rate = 90 Å/min
Time Constant = 1 sec
Wavelength Range: 4500 - 5200 Å (time runs from right to left; wavelength runs from left to right)
APRIL 27-28, 1963
4640Å
4686
4604
H-beta
4959 + 5007
17h 20m
LST
17h 15m
LST
100 Å

Figure 5

February 11 - April 7, these curves were determined by careful inspection of the appearance of emission and absorption line features on the scans, but the spectrum was so complex that these "continua" can only be regarded as approximations. Discussions of the records with Dr. D.B. McLaughlin were an integral part of this process, and in some cases his slit spectrograms of the nova were inspected to reinforce our judgment. The list of intensities in the continuum (Table 18) can be used to compare the continua assumed in this work with those that may be published by others. Since the continuum fades more rapidly than the general emission line spectrum (cf: McLaughlin 1960), and since amplifier gains were adjusted to keep the strongest lines in the spectrum on scale, the continuum is close to the dark level on records obtained after April 16th, so that errors in drawing it have very small effect on the measurement of intensities of the strong lines. (2) A smooth curve was drawn through the record of the emission line. In some cases, these curves were corrected for the effects of adjacent lines, by assuming (a) that the profile of the strong line in question should resemble those of other strong lines observed on the same night with the same spectral purity, and (b) that the line broadening is due to the expansion of the nova shell, through the Doppler effect, so that the total width at half-intensity of a given line should be

$$\Delta\lambda = (\Delta\lambda') \cdot \frac{\lambda}{\lambda'}$$

where $\Delta\lambda'$ is the width of an unblended line. In support of the latter assumption, we note that Baschek (1964) found that

$$\frac{\Delta\lambda'}{\lambda'} = .007 \pm 10\%$$

for all unblended emission lines measured on ten plates of the near infrared spectrum of Nova Herculis 1963 obtained between February 15 and July 5 with the 100-inch telescope at Mt. Wilson Observatory. The "4640" feature represents an exception not treated according to assumptions (a) and (b) (cf: section on Absolute Intensities of Emission Lines, this chapter). (3) The area above the assumed continuum defined by the smoothed emission line profile described above was measured with a planimeter and corrected for the effects of atmospheric extinction, instrumental sensitivity, amplifier gain, exit slit width and scan rate, as described below.

The atmospheric extinction laws and the instrumental sensitivity functions were determined primarily from observations of Vega and Deneb in nine 10.5 Å bands. Code (1960) has reported the intensities of these bands, relative to the intensity at 5560 Å. His data, in the form of "monochromatic magnitudes", that is, magnitudes per unit frequency interval for a bandpass of 10 Å are given in Table 5. We have assumed that the intensity in a given 10.5 Å band is

$$I_\lambda(10.5\ \text{Å}) = \frac{10.5}{10}\ I_\lambda(10\ \text{Å}),$$

so that the monochromatic magnitudes relative to 5560 Å are the same for both of these bandwidths.

Table 5

Monochromatic Magnitudes* (After Code 1960)

λ (Å)=	3860	4040	4190	4590	5060	5560	5810	6050	6670
Vega	-0.07	-0.19	-0.18	-0.14	-0.06	0.00	+0.06	+0.12	+0.22
Deneb	+0.05	+0.04	+0.05	+0.10	+0.01	0.00	+0.06	+0.18	+0.13

* Called m(1/λ) by Code.

On two nights, Vega was also observed in a tenth band, 6468 Å. At this wavelength,

$$m(1/\lambda) = +0.18$$

according to P.B. Boyce (private communication). Measurements of Vega and Deneb were combined by taking into account their respective energy distributions relative to 5560 Å (Table 5) and also the difference in their intensities at 5560 Å, which was taken to be

$$\Delta m\ (\ 5560\ \text{Å}\ ) = 1^{m}.23 \pm 0^{m}.02 \text{ est. p.e.}$$

in the sense that Vega is the brighter star. This quantity was determined from routine series of extinction observations taken on the two stars during two summers (Boyce and Maran, unpublished) and is identical to the difference in the V magnitudes (Johnson and Morgan 1953) of Vega and Deneb.

This agreement is expected for stars of roughly similar spectral class, since the effective wavelength of the V magnitude system is approximately 5465 Å.

Table 6 illustrates the method by which the standard star data were reduced. For this example, two typical measurements in the 10.5 Å band at 4590 Å, made on June 17-18, 1963, were selected.

Table 6

Reduction of Standard Star Observations

1	2	3	4	5	6	7	8
Star	L.S.T.	Controls	Gain	Defl.	M'	Air Mass	M(Vega scale)
Vega	$19^h44.^m0$	10^5,300,6	1.302	0.550	1.852	1.027	1.852
Deneb	$17^h15.^m0$	10^6,300,4	2.873	0.510	3.383	1.244	1.913

In Table 6, the names of the standard stars are given in the first column. Next are listed the local sidereal times of the measurements, which were interpolated between time marks placed on the observing records at intervals of about ten minutes. In the third column appear the gain settings of the apparatus. The first two quantities in this column represent the settings of the input resistance and voltage scale controls, respectively, on the GR 1230-A D.C. amplifier, and the third quantity is the setting of the relative gain control associated with the R-C network used to filter the signal before it is displayed on the Brown Recorder. The gain in magnitudes relative to a standard control setting of 10^5, 1, 6 (based on the calibration measurements des-

cribed by Boyce(1963)) is given in the fourth column. This quantity is added to that listed in the fifth column, namely the amplitude of the standard star signal expressed in magnitudes relative to full scale deflection on the Brown Recorder (conveniently measured with a "magnitude ruler" similar to that described by Hardie(1962)), in order to obtain M′ (sixth column). M′ (expressed in magnitudes) is the amplitude relative to full scale deflection, at the standard control setting, which corresponds to the apparent intensity of the standard star in the chosen bandpass and at the tabulated air mass[1] (seventh column). The air mass is given by

$$X = \sec z - c(z).$$

Sec z, the secant of the zenith distance, is taken from tables computed by R.G. Tull (unpublished) for the latitude of the McMath Reflector; c(z), the correction term required by the failure at large zenith distances of a plane-parallel model for atmospheric density variation, is tabulated by Hardie (1962). In the last column, the data are corrected to a common system, "M (Vega scale)", by subtracting from M′ (Deneb) the quantities $+0^m.24$ and $1^m.23$; the former is the difference in $m(1/\lambda)$ at 4590 Å for the two stars (cf: Table 5) and the latter is the difference in their brightnesses at 5560 Å, the zero point of the $m(1/\lambda)$ system.

[1] In the present context, the "air mass" is a dimensionless quantity, defined as the ratio of the number of terrestrial absorbing atoms per cm^2 column along a given line of sight to the number of such atoms per cm^2 along the line of sight to the observer's zenith.

The atmospheric extinction law for a given night was computed from the reduced standard star data. The procedure was as follows. For each of the nine 10.5 Å bands, the data on M (Vega scale) as a function of air mass were represented by a straight line of form

$$M(X) = M(X = 0) + K_\lambda \cdot X,$$

where X = air mass,

through the method of least squares. The slope of such a line,

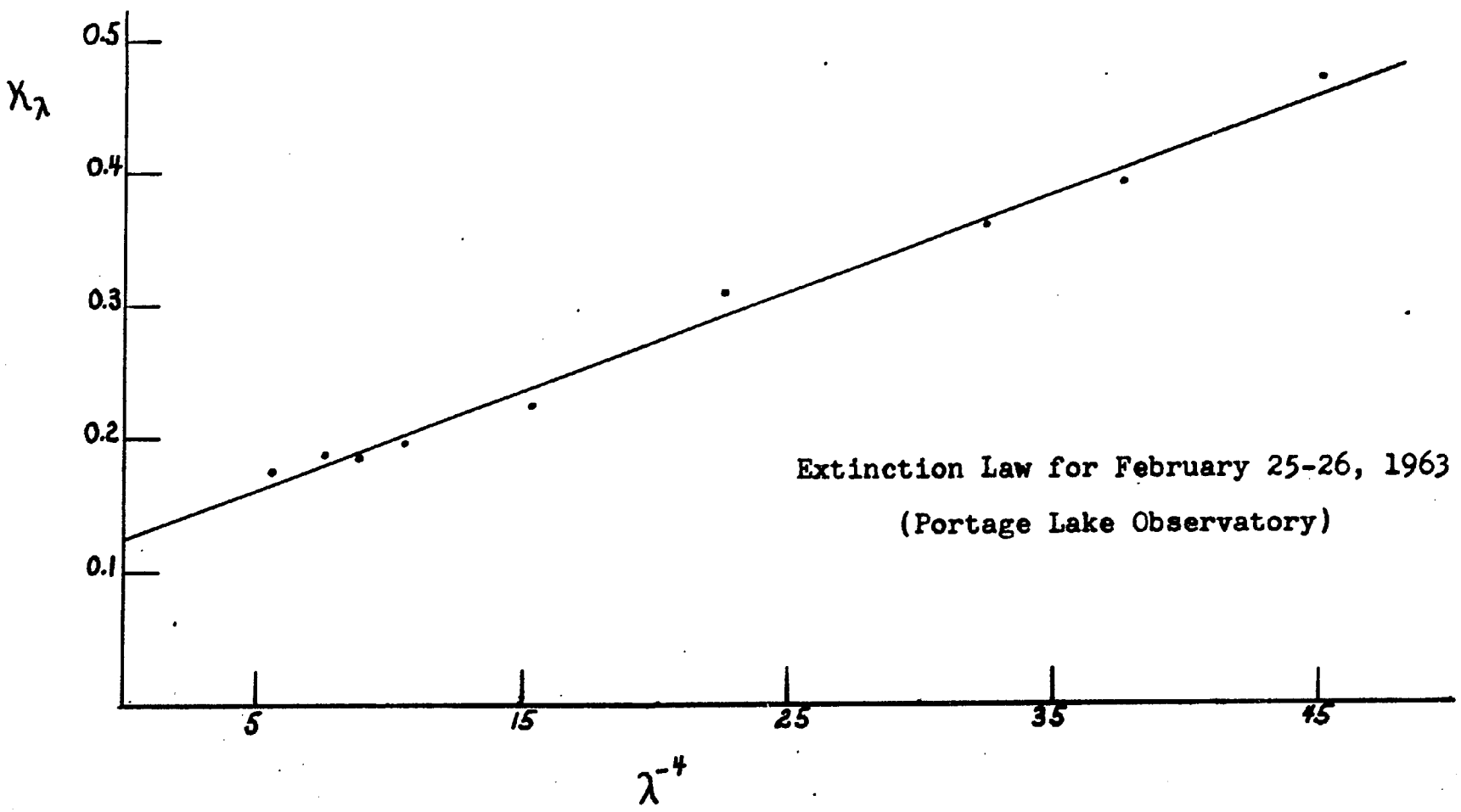
$$K_\lambda = \frac{n \sum XM(X) - \sum X \sum M(X)}{n \sum X^2 - (\sum X)^2},$$

where n = number of observations,

is called the monochromatic absorption coefficient. Ideally, the values of M (X) should be weighted (1) according to length of deflection on the chart and (2) inversely according to the zenith distance (Bertiau 1962), however these refinements were not attempted. In accord with Rayleigh scattering theory, it was found that within the wavelength range considered, the observed values of K_λ could be well represented by a straight line of form

$$K_\lambda = a + b \cdot \lambda^{-4},$$

in which λ is expressed in microns. Linear equations for K_λ as a function of λ^{-4} were therefore derived by the method of least squares; they are called "extinction laws". In Figure 6, a representative extinction law (the straight line) is compared with the observed



Extinction Law for February 25-26, 1963

(Portage Lake Observatory)

Figure 6

extinction coefficients (the dots) from which it was computed. Table 7 lists the a and b coefficients derived in this manner, as well as their probable errors.

A number of the nights on which observations of Nova Herculis 1963 were obtained were not by any means characterized by the atmospheric conditions which are usually felt to be required for accurate photoelectric work. Nevertheless, because of the importance of obtaining all possible information on the spectrum of the nova, especially in the early stages when it changed rapidly, we have attempted to reduce all of the observations, whether or not they were well calibrated. Data taken on the following nights must be especially suspect:

February 11-12 and 14-15: No suitable standard star data were obtained. Furthermore, an obvious systematic decrease in the transparency of the atmosphere occurred on each of these nights. The data were reduced (1) by assuming an extinction law whose coefficients a and b were equal to the unweighted mean values of the coefficients determined on the other observing nights, and (2) by arbitrarily assuming that this mean extinction law applied to the time when the first nova scan was begun on each night; measurements of features scanned at later times were corrected for the effects of the transparency decreases mentioned above by multiplying the observed intensities by "transparency correction factors". These factors, determined by plotting graphs of the apparent decrease with time of the intensity of a few strong emission lines that were scanned several times on each night,

Table 7

Atmospheric Extinction Coefficients

Date		a	p.e.	b	p.e.
(1963)					
Feb.	11-12	0.178*	---	0.0091*	---
	14-15	0.178*	---	0.0091*	---
	25-26	0.1260	0.0039	0.00739	0.00015
March	13-14	0.2117	0.0037	0.00935	0.00014
April	4-5	0.1035	0.0026	0.00750	0.00010
	6-7	0.2196	0.0041	0.00634	0.00016
	15-16	0.380	---	0.0091*	---
	21-22	0.2309	0.0098	0.00807	0.00044
	24-25	0.2079	0.0037	0.00876	0.00014
	26-27	0.388	0.016	0.01166	0.00063
	27-28	0.3612	0.0098	0.01009	0.00038
May	1-2	0.0992	0.0028	0.00963	0.00011
	5-6	0.239	0.012	0.00810	0.00037
	20-21	0.1315	0.0041	0.00771	0.00016
	23-24	0.1791	0.0063	0.01052	0.00025
	30-31	0.1905	0.0032	0.00869	0.00013
June	14-15	0.2742	0.0078	0.01276	0.00030
	17-18	0.1232	0.0076	0.00927	0.00030
	20-21	0.1125	0.0037	0.00742	0.00015
July	2-3	0.1147	0.0030	0.00814	0.00012
Aug. Sept.	31 - 1	0.0883	0.0044	0.01046	0.00019
Sept.	26-27	-0.0166	0.0050	0.01044	0.00021

*Assumed value.

were assumed not to be dependent on wavelength.

March 13-14: Comparison of Vega extinction data taken before and after the nova was scanned shows that a slight decrease in transparency had already begun by the time the nova observations were concluded. Six scans of the nova, #559 A - #559 F, were made on this night, and there was a twenty-minute pause between scans C and D due to the passage of a bank of cirrus. Based on inspection of both the Vega and nova observations, it is estimated that intensities determined from scans D, E and F, could be too low by $\lesssim$ 15%.

April 15-16: Definite large transparency fluctuations are evident in all of the Vega measurements except the first three deflections obtained on this night, which were all in the band at λ 6670 Å. The nova data were reduced by using the mean value of b determined from the other observing nights, and a value for a which followed from the λ 6670 Å data and the assumed b. However, the emission line intensities determined in this way were too low by a factor of about two, as compared with the values expected from the measurements made on other nights during April. Therefore, these intensities were multiplied by a correction factor of 1.8 given by the ratio of the expected intensity of H_β (from interpolation in Table 10) to the measured intensity.

September 26-27: The rather unlikely negative value of a (Table 7) is quite small in absolute magnitude but is nevertheless three times greater than its probable error. Actually, a small systematic transparency variation could

have caused this effect.

Once the extinction law for a given night is known it is a simple matter to determine the sensitivity function of the apparatus. First we compute

$$\overline{M\,(X=0)} = \frac{1}{n} \sum_i \left[M\,(X_i) - (K_{\lambda_{comp}}) \cdot X_i \right]$$

where the summation is over the n individual observations made at the given wavelength. Then we subtract the value of $\overline{M\,(X=0)}$ measured at 5560 Å from each of those measured at the other calibration wavelengths. We call the resultant quantities,

$$m_\lambda\,(X=0) = \overline{M_\lambda\,(X=0)} - \overline{M_{5560}\,(X=0)},$$

the "instrumental monochromatic magnitudes". The differences

$$S\,(1/\lambda) = m_\lambda\,(X=0) - m\,(1/\lambda)$$

between these quantities and the corresponding monochromatic magnitudes from Table 5 give us the instrumental sensitivity function, in magnitudes per unit frequency interval relative to the sensitivity at 5560 Å for an exit slit of constant width, $\Delta\lambda$. The absolute calibration is found by noting that the intensity received from Vega at zero air mass is

$$3.7 \times 10^{-9} \text{ erg/cm}^2\text{sec Å}$$

at 5560 Å, a value that follows from the V magnitude (Johnson and Morgan 1953) and the statement that a star

with V = 0.00 and B-V = 0.00 has an intensity of 3.8×10^{-9} erg/cm^{2}sec Å at 5560 Å (Code, 1960).

During the interval February 11-12 to July 2-3, the measured absolute sensitivity of the apparatus was constant to $\pm 0^m.03$ at all nine wavelengths. This function was identical to that measured by Boyce (1963) during the fall and winter of 1962, with one exception: the sensitivity measured in the present study at 4590 Å was consistently $0^m.06$ fainter than that found by Boyce. The high voltage supply to the photomultiplier was not adjusted in any way during this interval. After July 2-3, a slight upward drift in the high voltage supply occurred, and on the next observing night, August 31 - September 1, a significantly different sensitivity function was derived. The power supply was turned off for a short time in September, when repairs were necessitated by damage to cables by mice, and again a significantly different sensitivity function was obtained on the next (and last) observing night, September 26-27. The sensitivity function $S(1/\lambda)$, defined in the previous paragraph, is suitable for reducing data on measurements of the nova continuum, since it is expressed in magnitudes per unit <u>frequency</u> interval for a slit whose width is constant in wavelength units, and continuum intensities are normally expressed in erg/cm^2(c/s). However, the intensity of an emission line is usually expressed in erg/cm^{2}sec, since this quantity is determined by integrating under the line profile. Therefore, another sensitivity function was computed, namely

$$S(\lambda) = S(1/\lambda) - 2.5 \log (\lambda^2/\lambda_o^2),$$

where λ_o = 5560 Å. S (λ) is the sensitivity in magnitudes per unit wavelength interval relative to the sensitivity at 5560 Å. The instrumental relative sensitivity functions derived in this manner are given in Table 8. The corrections to place the data on an absolute scale are discussed below.

Table 8

Wavelength-Dependent Sensitivity

λ (Å)	Filter*	S(λ) Feb. 11-July 3	S(λ) Aug. 31-Sept. 1	S(λ) Sept. 26-27
3860	None	+ 1.^{m}41	+ 1.^{m}30	+ 1.^{m}24
4040	"	+ 0.72	+ 0.61	+ 0.62
4190	"	+ 0.28	+ 0.23	+ 0.22
4590	"	- 0.29	- 0.32	- 0.32
4590	Yellow	- 0.12	- 0.15	- 0.15
5060	"	- 0.31	- 0.32	- 0.31
5560	"	0.00	0.00	0.00
5810	"	+ 0.26	+ 0.24	+ 0.23
5810	Orange	+ 0.28	+ 0.26	+ 0.25
6040	"	+ 0.60	+ 0.58	+ 0.60
6468	"	-----	+ 1.35	+ 1.36
6670	"	+ 1.76	+ 1.78	+ 1.80

* Discussed by Tull (1963).

For convenience in making the reductions, all measurements of emission line intensities in Nova Herculis 1963 were transformed to a common system, corresponding to the following parameters:

Gain controls: 10^6, 1, 6

Exit slit width: 10.5 Å

Scan rate: 90 Å/min

Recorder chart transport rate: 2 inches/min

and were corrected for the effects of atmospheric extinction and instrumental sensitivity. The following table gives an example of such a reduction, for two lines measured on April 6-7, 1963.

Table 9

Reduction of Emission Line Intensities

(1)	(2)	(3)	(4)	(5)	(6)
H_β	101.5	$15^h52^m.5$	1.111	.3332	1.406
H_α	110.2	$16^h07^m.0$	1.088	.2538	1.290

(1)	(7)	(8)	(9)	(10)	(11)	(12)
H_β	.04103	1.	0.7762	3.	1.	16.3
H_α	.04103	1.	4.112	3.	1.	86.1

Column (1) gives the line identification; the area under the line profile, expressed in dial units of the planimeter (the same planimeter was used for all reductions), is listed in column (2); the L.S.T. of observation appears in column (3) and the corresponding air mass, X, in column (4). The extinction coefficient,

$$\kappa_{\lambda\,\mathrm{comp}} = a + b\,\lambda^{-4},$$

where a and b are taken from Table 7, is given in column (5). The "extinction ratio", or factor by which each measured area must be multiplied in order to correct the intensity to zero air mass, is given by

$$\text{Ext. Ratio} = \text{Antilog}\ \left[0.4\ \kappa_{\lambda} \cdot X\right],$$

and is listed in column (6). Both of these measurements were taken with the gain controls set at 10^6, 100, 8; the corresponding ratio necessary to convert the data to the standard gain setting of 10^6, 1, 6 is shown in column (7). The correction factor for the exit slit width (column (8)) is unity for these data because the standard width of 10.5 Å was employed. $S(\lambda)$, the sensitivity function (in magnitude units), defined by Table 8, can be transformed by the relation

$$S(\lambda)_{\mathrm{Ratio}} = \text{Antilog}\ \left[0.4\ S(\lambda)\right] \quad .$$

to $S(\lambda)_{\mathrm{Ratio}}$, which is the ratio of the sensitivity at a given wavelength to the sensitivity at 5560 Å. Values of $S(\lambda)_{\mathrm{Ratio}}$, interpolated between the calibration wavelengths, are given in column (9). The ratio of the scan rate to the standard rate of 90 Å/min is given in column (10), and the ratio of the recorder chart transport rate to its standard value is given in column (11). Finally, the product of the quantities in columns (2), (6), (7), (8), (9), (10) and (11) represents the area in planimeter scale units that

would be obtained with our apparatus in the absence of atmospheric extinction, with the controls at the standard settings, and if the sensitivity of the system at each wavelength were equal to the sensitivity measured at 5560 Å. This quantity is then multiplied by the absolute sensitivity of the system at 5560 Å (determined from measurements of Vega),

$(1.20 \times 10^{-9}$ erg/cm^{2}sec) per planimeter scale unit,

in order to obtain the intensity of the emission line. This absolute intensity is given in column (12) in units of 10^{-9} erg/cm^{2}sec. 15.5 planimeter scale units correspond to an area of 1 cm^2. The quoted sensitivity refers to the interval February 11-12 to July 2-3; corresponding values for the other two observing nights are:

Aug. 31 - Sept. 1

$(1.12 \times 10^{-9}$ erg/cm^{2}sec) per planimeter scale unit

Sept. 26-27

$(1.30 \times 10^{-9}$ erg/cm^{2}sec) per planimeter scale unit.

Continuum intensities are reduced in a similar manner. S $(1/\lambda)$ is used instead of S (λ), as the desired intensities are in terms of erg/cm^{2}sec (c/s). Further, no corrections are made for scan rate and recorder chart transport rate, since the measured quantity is a deflection rather than an area.

There is one exception to the procedure described above. Due to an impedance mismatch between the amplifier and the R-C network, it was impossible to calibrate the gain employed on February 11-12. Therefore the data were reduced on an arbitrary scale and then calibrated by linear extrapolation of the intensity of the first four lines of the Balmer series and also five lines of Fe II. The calibration factors derived separately from these two sets of lines differed by one part in 40.

The observed intensities of emission lines and the continuum, determined in the manner just described, are reported in the following section.

Absolute Intensities of the Emission Lines

The spectrum of a nova undergoes marked changes with the passage of time. Several different stages in the spectral development of novae have been distinguished on the basis of radial velocity measurements, line identifications and the general appearance of the spectrum. These are reviewed by McLaughlin (1960). The photoelectric scans obtained in the present investigation refer to three of the spectral stages:

Principal Spectrum: During this stage the chief features in the emission line spectrum, as recorded on the scans, were the lines of the Balmer Series, permitted lines of Fe II, Si II, N II and Cr II, and forbidden lines of [N II] and [O I]. The principal spectrum dominated the records taken on four observing nights:

February 11-12

February 14-15

February 25-26

March 13-14.

Orion Spectrum: This stage is characterized by broad, hazy, complex emission. Due to the intrinsic blending in the nova spectrum, as well as to the limited resolution of the spectrophotometer, relatively few individual lines can be distinguished on the scans. The new emission features that appeared in this stage were largely due to N II and O II. The Orion spectrum was recorded on two nights:

April 4-5

April 6-7

Nebular Spectrum: The dominant new features in this phase were the lines of [O III] , N III and He II. This was the best observed stage; the nebular spectrum was recorded on sixteen nights in the interval April 15 to September 27.

Typical scans of the Principal, Orion and Nebular spectra are shown in Figures 3, 4 and 5, respectively.

Our photoelectric scans have, at best, a resolution of 10.5 Å. Further, the wavelength calibration is rather crude. Therefore, identifications for the measured emission lines have been assumed on the basis of spectroscopic investigations of previous novae, especially those of Beer (1936) and McLaughlin (1937), who studied Nova DQ Herculis 1934, and that of Wyse (1939), who studied Nova V603

Aquilae 1918. Many of these identifications are not completely certain. The uncertainty arises from several related factors, namely the simultaneous presence of several velocity systems, the great breadth of the lines, and the blending intrinsic in novae spectra.

The measured absolute intensities of the emission lines, as observed at the Earth and corrected for atmospheric absorption, are given in this section. For convenience of presentation, and also to facilitate comparison of the data with the physical quantities calculated in the next chapter, the dates of observation are given in terms of

$$t = \text{days since January 26, 1963,}$$

the time elapsed since the date at which the expansion of the nova shell is assumed to have begun. The observed intensities are given in units of 10^{-9} erg/cm^{2}sec.

Table 10 presents the measured intensities of the lines of the Balmer series of hydrogen, that were recorded throughout the 227 day period of observation. Several comments are in order with respect to these data:

H_ϵ and H_ζ : Due to the low instrumental sensitivity in this region of the spectrum, the response areas of these two lines rarely exceeded 1 cm^2 on our records. Therefore, the data are very uncertain. 3969 Å Ca II was a probable contributor to the H_ϵ intensity in the Principal stage, and later the contributions of [Ne III] and He II, both at 3969 Å may have been important. In the Nebular stage,

Table 10

Measured Intensities of the Balmer Lines

t*	H_α	H_β	H_γ	H_δ	H_ϵ	H_ζ
		(Unit = 10^{-9} erg/cm^{2}sec)				
17	330.	110.	31.	17.	14.	5.9
20	-----	98.	30.	19.	16.	5.3
31	172.	48.9	22.0	12.6	8.2	4.2
47	96.3	15.5	7.45	6.55	3.8	1.2
69	83.7	17.8	10.5	10.1	5.82	1.7
71	84.9	16.1	-----	-----	-----	---
86	68.2	16.1	-----	-----	-----	---
89	-----	16.5	-----	-----	-----	---
91	65.3	15.6	7.8	8.44	3.62	3.6
92	66.7	14.7	8.2	8.98	3.20	2.7
96	52.1	13.2	6.6	7.72	2.81	2.8
100	-----	13.6	-----	-----	-----	---
115	30.2	8.41	3.8	5.30	-----	---
118	29.2	8.38	3.8	3.89	-----	---
125	22.1	6.24	3.2	3.81	1.27	---
140	17.7	-----	-----	-----	-----	---
143	16.2	4.63	2.5	2.27	1.24	---
146	13.5	4.37	-----	-----	-----	---
158	9.30	3.01	1.8	-----	-----	---
218	2.38	0.86	0.4	-----	-----	---
244	1.38	0.80	-----	-----	-----	---

* Time in days since January 26, 1963.

3869 Å [Ne III] was probably an important contributor to the H_ζ intensity.

H_δ : By t = 47^d (March 13-14), 4097, 4103 Å N III had probably become major contributors to the measured intensity of this line. The profiles of H_δ in the Nebular stage were corrected for the presence of adjacent emission on the blue side, probably due to 4069-76 Å O II.

In the Orion stage, correction was made for a blended emission on the red wing, probably due to 4133 Å O II. In the Nebular stage, the poor signal-to-noise ratio made it difficult to trace the profile of H_δ, and it was impossible to correct for this weak feature on the red wing, if in fact it was still present.

H_γ : In the Principal and Orion stages, this line was corrected for the effect of blending with 4352 Å Fe II on the red wing. In the Nebular stage, correction was made for blending with 4363 Å [O III], which always had an equal or greater response area.

H_α : A very small correction was made for the effect of blending with a weak feature whose wavelength, measured from the scans, was

$$\lambda = (6605 \pm 10)\ \text{Å}.$$

This feature was present from the first night of observation until t = 146^d; if it was present thereafter it could not

have been detected on our records due to the poor signal-to-noise ratio. There is great scatter in the measurements of this feature due to the very small response area and also the presence of H_α nearby. The data can best be summarized by stating that over the interval $t = 17^d$ to 146^d, the intensity of this feature was

$$I\ (6605\ \text{Å}) = (0.035 \pm 0.025)\ I\ (H_\alpha).$$

There can be no doubt of the reality of this line, since it appears on the red wing of H_α on scans taken in both the forward (toward longer wavelengths) and reverse directions. No identification for this feature can be proposed on the basis of the crude wavelength measurement given here, but the possibilities include (1) a high velocity component of H_α ; (2) 6583 Å [N II] ; (3) 6599 Å [Fe VII] . No line near this position is reported by Andrillat and Bloch (1963). Also, no such line is listed by Baschek (1964), but H_α was greatly overexposed on his spectrograms of Nova Herculis 1963.

No important blends occurred on the wings of H_β . However, Bashkin and Meinel (1964), who produced artificial novae spectra in the laboratory, suggest that 4857 Å N III may be an important contributor to this line.

The intensities of 6300, 6364 Å, the red [O I] lines, were measured on three nights. The results are given in the following table:

Table 11

Measured Intensities of the [O I] Lines

t*	λ = 6300	6364
	(Unit = 10^{-9} erg/cm^{2}sec)	
47	2.3	2.2
69	1.1	1.2
71	1.1	2.3

* Days since January 26, 1963.

These data are uncertain due to the small response areas involved, but 6364 Å apparently was roughly equal to or greater than 6300 Å on all three nights. Since the predicted ratio

$$\frac{I\ (6300)}{I\ (6364)} = 3.1$$

(Garstang 1951), the photoelectric observations are in accord with Baschek's (1964) statement that 6364 Å is blended with 6374 Å [Fe X], the "red coronal line". An alternative identification (6347-71 Å Si II) is suggested by Bloch and Chalonge (1964), but the persistence of the emission blended with 6364 Å until at least t = 160^d (Baschek 1964) supports the [Fe X] identification. Perhaps both Si II and [Fe X] made significant contributions to "6364 Å", but at different times. From the observed intensities of 6300, 6364 Å and the theoretical ratio given above, we can derive approximate values for the intensity of the line that is blended with 6364 Å:

Table 12

Estimated Intensities of 6374 Å [Fe X] and/or 6347-71 Å Si II

t*	I (10^{-9} erg/cm^{2}sec)
47	1.5
69	1.
71	2.

The intensities of the strong permitted and forbidden lines of N II, 5680 and 5755 Å, respectively, are summarized in Table 13. 5680 Å was measurable from the first night of observation until t = 143^d, well into the Nebular stage, and 5755 Å was still measurable on the last night of observation. A graph of the ratio

$$\frac{I\ (5755)}{I\ (5680)}$$

(Figure 7), shows a striking maximum near t = 71^d, during the Orion stage. Wyse (1939) discussed the fluctuations in this ratio associated with oscillations in the light curve of Nova V603 Aquilae 1918. No oscillation is apparent at t = 71^d (J.D. 2,438,127) in the A.A.V.S.O. light curve for Nova Herculis 1963, however (Figure 1), although a slight local maximum seems to have ended a few days previously. Further, the two lines seem less well resolved on scans taken at t = 69^d and 71^d than on both earlier and

Table 13

Measured Intensities of 5680 Å N II and 5755 Å [N II]

t*	λ = 5680	5755
	(Unit = 10^{-9} erg/cm^{2}sec)	
17	2.4	1.3
20	6.5	7.4
31	2.84	4.14
47	6.12	8.75
69	4.69	9.82
71	3.28	11.5
80	2.39	7.34
86	2.36	5.14
89	2.72	4.01
92	2.35	3.11
96	1.80	2.55
100	1.59	1.75
115	----	1.95
118	0.68	2.42
125	0.58	3.12
143	0.39	2.67
244	----	0.37

* Days since January 26, 1963.

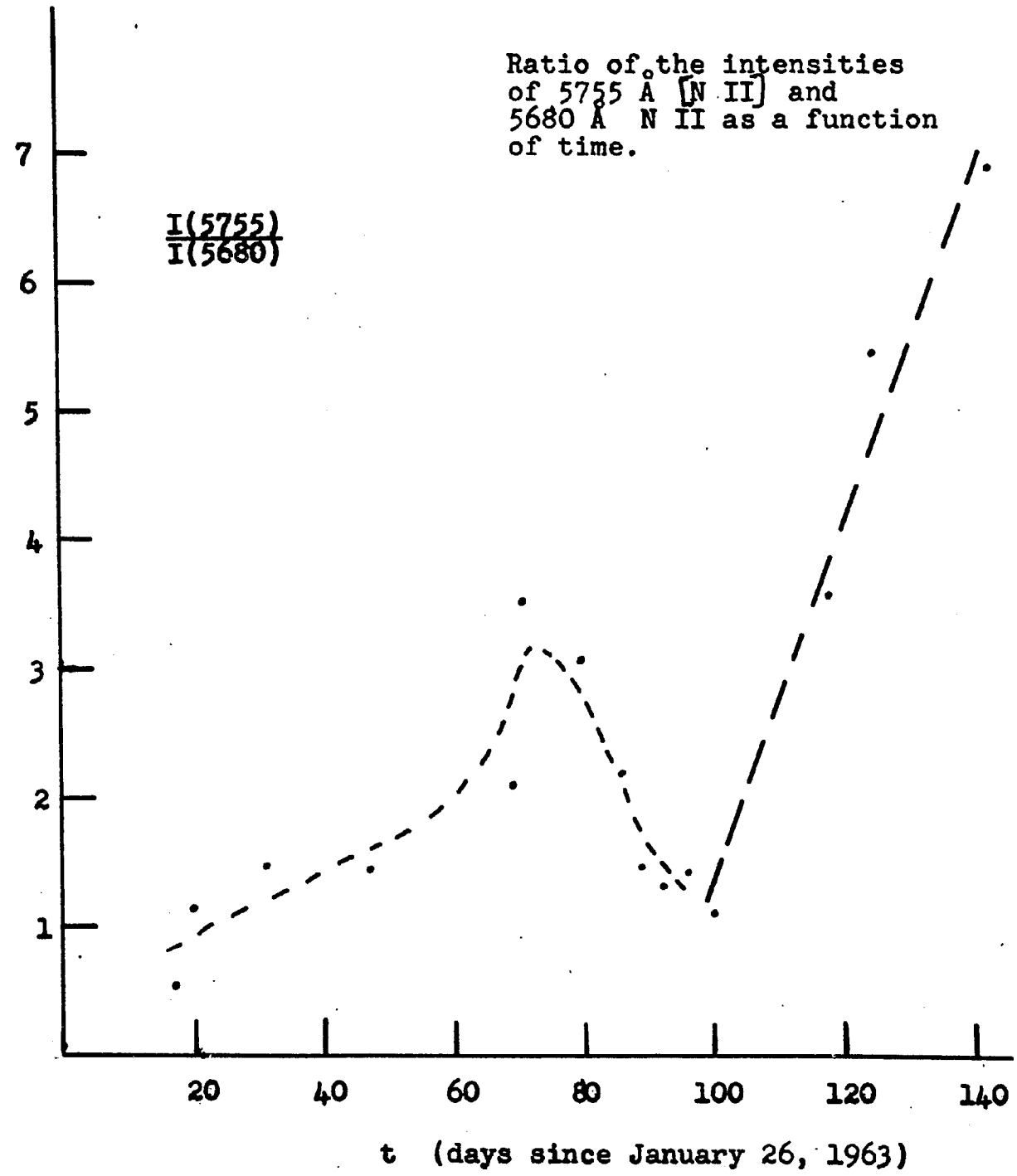

Ratio of the intensities of 5755 Å [N II] and 5680 Å N II as a function of time.
I(5755) / I(5680)
7
6
5
4
3
2
1
20
40
60
80
100
120
140
t (days since January 26, 1963)

Figure 7

later records. Therefore, it seems possible that some other line(s) contributed to the emission in this region during the Orion stage. Perhaps the N II lines at 5711, 5731, and 5747 Å may be responsible for this effect. Note (Table 13) that the measured intensities of both 5680 and 5575 Å were quite low on t = 31^d. On this date (Figure 1, J.D. 2,438,087), the nova was close to a secondary maximum, but there is no obvious corresponding fluctuation in Figure 7. It was difficult to estimate the level of the continuum on our scans in this spectral region on t = 31^d; therefore the possibility that the intensities of 5680, 5755 Å were systematically underestimated must be considered.

The lines 6456 Fe II and 6482 N II are blended on our records, and the measurements, presented in Table 14, are uncertain due to the small response areas. Presumably, Fe II was the chief contributor at first, but N II must have been dominant in the Orion stage. This feature was not measurable after t = 71^d.

Table 14

Measured Intensities of 6456 Å Fe II + 6482 Å N II

t*	I (10^{-9} erg/cm^{2}sec)
17	3.8
31	2.9
47	3.7
69	2.7
71	2.8

* Days since January 26, 1963.

Absolute intensities for those lines measured in the Principal spectrum but not discussed above are listed in Table 15. These emissions are due to Fe II, with the following exceptions:
4630 Å Fe II is blended with 4641-61 Å O II;
emission at 4824,36,48 Å is due to Cr II;
emission at 5041,56 Å is due to Si II.

Absolute intensities for lines measured in the Orion spectrum are given in Table 16. Most of these features are very wide and represent blends of a number of lines. Therefore the identifications cannot be considered certain. The wavelengths listed in Table 16 are very approximate. An attempt to list the most likely contributors to these emissions follows: (after McLaughlin 1937)

λ (Å)

4520: 4508,15,23,49,56 Å Fe II;

4650: probably largely 4641,49,61,76,96 Å O II but 4713 Å He I, 4686 Å He II, and 4643 Å N II may also contribute;

4790: 4774,88,93 and 4808 Å N II;

4930: 4895 Å N II, 4924 Å Fe II, and 4943,55 Å O II;

5005: 4994 Å N II, 4924 Å Fe II, 5045, 5104 Å N II;

5170: 5133,45 Å C II, 5158 Å [Fe II], 5160 Å O II, 5169,98,5235 Å Fe II;

5315: 5273 Å [Fe II], 5276,84,5317 Å Fe II, 5321,51 Å N II, 5330 O I;

Table 15

Measured Intensities of Emission Lines - Principal Spectrum

t*	λ =	4173,79	4352	4630,50	4731	4824-48	4924	5018	5041,56	5169	5317
17		5.5	2.0	11.	3.6	5.5	17.	23.	3.8	16.	----
20		3.1	----	14.	3.7	7.0	16.	25.	3.6	13.	5.9
31		0.90	1.7	7.9	4.6	7.2	12.0	16.9	3.9	9.34	3.45
47		----	0.88	9.5	3.9	2.8	5.1	8.6	2.1	3.67	----

* Days since January 26, 1963.

ONE INTENSITY UNIT = 10^{-9} ERG/CM^{2}SEC.

Table 16

Measured Intensities of Emission Lines - Orion Spectrum

λ	t* = 69	71
	(Unit = 10^{-9} erg/cm^{2}sec)	
4520	3.92	3.4
4650	21.6	21.2
4790	1.42	0.86
4930	3.69	3.53
5005	8.51	6.24
5170	2.20	1.2
5315	1.93	1.4
5910	3.2	2.1

* Days since January 26, 1963.

5910: 5854 Å Al II, 5876 Å He I, 5890-96 Å Na I, 5932,42,52 Å N II, 5959 Å O I.

Absolute intensities measured in the lines of the Nebular spectrum are presented in Table 17. The identifications are as follows:

λ(Å)

4267: C II;

4363: [O III] ;

4511-35: N III;

4604: N V;

4640: chiefly N III, but perhaps also N II and fading O II of the Orion spectrum;

4686: He II; perhaps also 4713 Å He I;

4774-4810: N II;

4959 + 5007: [O III] ;

5016: 5015 Å He I and 5018 Å Fe II;

5169: Fe II was probably very weak; likely contributors include 5147,77 Å [Fe VI] , 5152 Å [Fe III] , 5158 Å [Fe VII] , and 5158,59,64,82,85 Å [Fe II] (Bloch 1950);

5876: He I.

The data on 4363 and 5016 Å are uncertain due to blending with H_γ and 5007 Å, respectively. The data on 4604, 4640 and 4686 Å must also be regarded as uncertain

Table 17

Measured Intensities of Emission Lines - Nebular Spectrum

t*	λ =	4267	4363	4511-35	4604	4640	4686	4774-4810	4959 + 5007	5016	5169	5876
80		----	----	----	----	20.†	----	----	20.	----	----	----
86		----	----	----	----	10.‡	1.5	1.20	25.6	0.67	0.60	----
89		----	----	1.01	----	14.‡	1.4	0.42	26.6	0.65	0.68	----
91		0.53	7.5	0.76	1.4	9.1	2.2	0.76	28.1	1.2	0.80	----
92		----	7.9	0.66	1.6	10.2	2.6	----	26.6	1.3	0.49	----
96		----	7.3	0.72	1.6	9.0	2.5	----	24.6	1.6	0.55	1.9
100		----	----	1.1	----	----	----	0.42	25.9	1.2	0.53	1.6
115		----	6.7	----	----	5.9	2.2	----	17.9	----	----	0.8
118		----	7.3	----	0.54	5.7	1.8	----	20.4	0.62	----	1.0
125		----	6.5	----	0.25	4.2	1.5	----	17.1	0.76	----	0.84
143		----	5.8	----	0.45	3.0	1.2	----	17.2	0.43	----	0.55
146		----	----	----	----	----	----	----	16.5	0.43	0.2	----
158		----	5.2	----	0.20	2.0	0.59	----	16.1	0.22	----	----
218		----	1.8	----	----	----	----	----	11.5	----	0.3	----
244		----	----	----	----	0.65	0.34	----	10.2	----	----	----

*Days since January 26, 1963. †Includes 4604 and 4686. ‡Includes 4604.
ONE INTENSITY UNIT = 10^{-9} ERG/CM^{2}SEC.

due to blending. 4640 Å is particularly difficult to correct for blending because neither wing is blend-free. Further, in order to draw reasonable profiles for 4604 Å and 4686 Å, it was necessary to assume that 4640 Å had a somewhat greater half-width than that predicted from other strong lines according to the procedure discussed in the Reductions section. This can be explained as due to unresolved emission of 4634 Å N III. On records obtained during the first few observing nights of the Nebular phase, it was not possible to resolve the complex at 4604-4686 Å (see Table 17), because the broadly flared N III Orion emission was still present.

The internal probable errors of the emission line intensity measurements, as estimated from the scatter in readings taken on a given night, range from less than 10 per cent for the strongest, not significantly blended lines such as H_α , H_β and 4957+5007 Å, to roughly 50 per cent for the very weak features such as the unidentified line at 6605 Å. Of course, the uncertainty is greater for data taken on "bad" nights (cf: section on Reduction of Observational Data, this chapter). Data taken on February 11-12, February 15-16, and April 15-16 ($t = 17^d$, 20^d, 80^d, respectively) may contain systematic errors due to the assumptions involved in the extinction corrections and calibration. The signal-to-noise ratio of course decreased as the nova faded, but it was possible to compensate, at least

partially, for this effect because the generally better weather conditions in the summer of 1963 allowed us to take more scans of a given spectral region per night.

Absolute Intensities in the Continuum

These data are very uncertain and are presented in Table 18 primarily as an indication of what continuum level was assumed on a given night (cf: section on Reduction of Observational Data). It is not claimed that the wavelengths of measurement were located in "windows" free of lines. In fact, readings are listed for the Balmer wavelengths.

The Moon was always $> 50°$ from Nova Herculis 1963 when the scans used for continuum measurements were made, and readings taken at a few wavelengths in the visual region just before and after the nova observations were secured showed that the sky brightness made no measurable contribution. Sky readings were not taken when the nova faded and the continuum was no longer being measured, since measurements of emission-line intensities are not affected by the presence of an extraneous continuum. Several years of experience with the McMath telescope and Tull spectrophotometer have shown that the only detectable contribution of the sky is a continuous spectrum, except during the occurrence of bright aurorae, when emission of 5577 Å [O I] is observed.

Table 18

Intensities of Assumed Continua

λ t* =	17	20	31	47	69	71
H_α	4.8	---	5.0	1.2	0.65	1.0
6388	4.4	---	4.9	1.2	0.63	0.83
6203	4.5	---	---	---	---	---
6055	4.2	---	---	---	---	---
5452	3.8	4.7	5.2	0.80	0.60	---
H_β	4.2	4.0	4.2	0.92	0.52	0.34
4741	4.3	4.2	4.4	1.0	0.55	0.36
4609	4.6	4.7	4.7	1.1	0.61	0.41
4401	4.8	7.4	5.1	1.6	0.75	---
H_γ	4.7	6.2	5.2	1.6	0.71	---
4149	4.2	6.6	5.1	1.5	0.65	---
H_δ	4.7	6.1	5.4	1.6	0.68	---
4036	4.7	7.0	5.5	1.6	0.74	---
H_ϵ	5.1	7.4	6.1	1.7	0.83	---
3920	5.1	7.3	6.0	1.6	0.90	---
H_φ	5.5	8.2	6.1	1.7	0.92	---

*Days since January 26, 1963. ONE INTENSITY UNIT = 10^{-22}ERG/CM^2 SEC (C/S)

CHAPTER III

PHYSICAL INTERPRETATION

Distance and Interstellar Reddening

The measured intensities of the emission lines and continuous spectrum presented in Chapter II must be corrected for wavelength-dependent attenuation by the interstellar medium ("interstellar reddening") before they can be used to determine physical properties of the nova. Further, knowledge of the distance to the nova is required for the determination of some properties of the nebular shell (e.g.: N_e, the number density of electrons) by the method of Pottasch (1959c,d). In principle, N_e and the electron temperature of the shell, T_e, can be found from measurements of

$$\mathcal{R} = \frac{\text{I (auroral transitions)}}{\text{I (nebular transitions)}}$$

for each of two ions (Aller and White 1949). The results from this method are affected by the reddening but not by the distance. However, the necessary data were obtained for only one ion (O^{++}) in the present study.

Payne-Gaposchkin (1957) and McLaughlin (1960) have reviewed the ways by which distances to novae have been determined. These methods are:

(1) comparison of the angular rate of nebular expansion with the radial velocity, determined spectroscopically;

(2) use of the total equivalent width of the interstellar Ca II lines as a distance indicator;

(3) interpretation of the radial velocities of the interstellar Ca II lines in terms of the galactic rotation effect;

(4) measurement of annual and secular parallaxes.

Method (1) involves the assumption that the expansion of the nova shell is spherically symmetrical, which is doubtful in certain cases. However, it is the most reliable of the four techniques listed above. Methods (2) and (3) are inaccurate due to the inhomogeneous and to some extent unknown distribution of the interstellar gas. They are especially unsatisfactory for stars far from the galactic plane, such as Nova Herculis 1963, which has a galactic latitude, b^{II}, of + 24°. The annual parallaxes which have been reported for novae are so uncertain that they can only be discussed statistically, and the secular parallaxes are considered to be erroneous because they imply an unlikely position for the solar apex (McLaughlin 1942).

A less direct method for estimating the distance of a nova is suggested by Pottasch (1959c). He showed that the

mass of hydrogen in the shell, as determined when the gas is optically thick in Hα , is proportional to the fourth power of the assumed distance. However, when the shell is optically thin in Hα , the computed mass depends on the first power of the distance. The distance found by this method is that for which the masses of hydrogen, as determined for these two cases, are equal. However, this method depends critically on the assumed geometry of the nebular expansion; also, the determination of the mass of hydrogen in case (a) is based on a relation between N_e and I (Hα) that must be regarded as at best a crude approximation.

The visual absolute magnitude of a nova can be found from the observed apparent magnitude (m_v) and the estimated distance (r) by means of the usual equation

$$M_v = m_v + 5 - 5 \log r - A_v \quad , \qquad (1)$$

where A_v is the interstellar absorption expressed in magnitudes, and r is in parsecs. It is found empirically that M_v is related to the shape of the light curve (McLaughlin 1945). McLaughlin (1960) has recently rediscussed this relation, using distances determined by methods (1) and (2). He finds that the data are fitted best by

$$M_{v_o} = -11.5 + 2.5 \log t_{3,v} \quad , \qquad (2)$$

where M_{v_o} is the visual absolute magnitude at maximum light and $t_{3,v}$ is the duration in days of the decline through three visual magnitudes from maximum.

Batten, Richardson and Wright (1963) find

$$r \approx 500 \text{ pc}$$

for Nova Herculis 1963, by method (2). However, as mentioned above, this technique yields very uncertain distances.

From Figure 1, it follows that

$$m_{v_o} \approx 3^m.$$

and

$$t_{3,v} \approx 36 \text{ days},$$

where m_{v_o} is the visual apparent magnitude at maximum light. Then from equation (2),

$$M_{v_o} \approx -7.6 \quad .$$

In the present study, the value

$$A_v = 0^m.2$$

is adopted for a reason discussed below, and equation (1) yields the distance,

$$r \approx 1200 \text{ pc},$$

used in subsequent sections of this chapter.

Studies of the light curves of novae in Messier 31 (Hubble 1929; Arp 1956) and in the Magellanic Clouds (Buscombe and de Vaucouleurs 1955) show that relations similar to equation (2) also hold in those galaxies. This supports the view that equation (2) expresses an intrinsic property of the nova phenomenon. Thus, the distance derived from equations (1) and (2) is probably entitled to more weight than that found by Batten et. al. The systematic errors in the physical parameters of the nova that would arise from the adoption of incorrect values of A_v and r are considered in Chapter IV.

The wavelength dependence of interstellar reddening is given by Whitford (1958) in the form of a graph that can be calibrated if the absolute value of the absorption is known for at least one wavelength. In the present study, this reddening law is used with the assumption that the visual absorption is

$$A_v = 0^m.2.$$

This value is very uncertain. It follows from the observed relation (Schmidt 1958) between linear polarization and interstellar absorption,

$$\left(\frac{p}{A_v}\right)_{max} = 0.065 \pm 0.005 \text{ m.e.},$$

where $$p = 2.5 \log \frac{I_{max}}{I_{min}} \text{ magnitudes},$$

and Clarke's (1964) measurement of P, the degree of linear polarization, for Nova Herculis 1963:

$$P = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = 0.006 \pm 0.002.$$

In order to determine the physical properties of the nova, the observed intensities given in Chapter II are corrected for interstellar reddening by multiplying them by the factors

$$A_\lambda \text{ (ratio)} = \text{Antilog } \left[0.4\ A_\lambda \text{ (mag.)} \right]$$

determined from the Whitford reddening law and the adopted value of A_v. A_λ (ratio) ranges from 1.15 (for Hα) to 1.30 (for Hγ).

Geometry of the Nova Shell

Pottasch (1959a,c,d) has proposed a quantitative model for the phenomena observed after a nova outburst occurs. His theory is based on McLaughlin's (1942) interpretation of the photometric and spectroscopic behavior of seven well-observed novae. For the purposes of the present study, the chief point of this model is the source of the emission lines observed in the Principal and Nebular spectra. These lines are considered to originate in a shell that recedes from the star at the velocity associated with the Principal spectrum. Thus, the radius of the shell is given by

$$R\ (t) \approx \bar{V}_p t, \qquad (3)$$

where $\bar{V}_p$ is the mean radial velocity of the Principal spec-

trum, t is the time elapsed since the shell was detached from the star, and it is assumed that

$$R\ (0) << \quad R\ (t).$$

Pottasch (1959a,c) states without reference that the thickness of the shell is given by

$$\Delta R\ (t) = \frac{2V_s t}{\gamma - 1} \qquad (4a)$$

where V_s is the velocity of sound and γ, the usual ratio of specific heats

$$\gamma = c_p/c_v\ ,$$

is equal to 5/3 for a monatomic gas. However since

$$\frac{2\ V_s}{\gamma - 1}$$

is the rate at which an initially homogeneous interstellar cloud expands into free space (Burgers 1946), the nova shell should have the following thickness, because expansion will take place at both surfaces of the shell:

$$\Delta R\ (t) \approx \frac{4V_s t}{\gamma - 1}\ , \qquad (4b)$$

if $$\Delta R\ (0) << \quad R\ (t)\ .$$

McVittie (1950 and 1951) and Copson (1950) have criticized Burgers' result; it is adopted here as an approximation. The shell will be thicker than suggested by equation (4b) if the ejection is not an instantaneous process. In the present study, $\Delta R\ (t)$ is computed from equation (4b), assuming that

$$T_e = 10{,}000\ ^\circ K$$

whence $$V_s = \sqrt{\frac{P\gamma}{\rho}} \approx 1.66 \times 10^6 \text{ cm/sec},$$

where the pressure,

$$P \approx \left[N_e + N\,(H)\right] k\, T_e\ ,$$

and the density,

$$\rho \approx N\,(H)\,\mu\,(H).$$

N (H) is the density of hydrogen in all states, and μ (H) is the mass of a hydrogen atom. R (t) is computed from equation (3), using the value

$$\bar{V}_p = 1000 \text{ km/sec},$$

which was determined from radial velocity measurements of University of Michigan spectrograms (McLaughlin, private communication). The result is that

$$R\,(t) = 10\Delta R\,(t).$$

Baade's measurements (van de Hulst 1951) of direct photographs of Nova V603 Aquilae 1918 show that $\Delta R/R$ was constant and equal to 0.09 over an interval of 18 years. For that nova, (taking $\bar{V}_p$ = 1700 km/sec and $V_s = 1.66 \times 10^6$ cm/sec), $\Delta R/R$ would be 0.06 according to equation (4a) and 0.03 according to equation (4b).

Ratio of the Number Densities of Protons and Electrons

Most of the published theoretical work on the intensities of permitted emission lines in nebulae is strictly applicable only at electron densities less than 10^4 cm^{-3}. Jefferies and Pottasch (1959) have considered the more general case where detailed account is taken of collisional as well as radiative processes, in order to calculate the

emergent intensity of Hα for an optically thin nebula of arbitrary electron density. In a subsequent section of this Chapter, their results are used to calculate N_e and T_e. For that purpose, however, it is necessary to know the ratio

$$\frac{N(H^+)}{N_e}$$

of the number densities of protons and electrons. For the conditions expected to prevail in a nebula, only hydrogen and helium make significant contributions to N_e and hence

$$\frac{N(H^+)}{N_e} = \left[1 + \frac{N(He^+)}{N(H^+)} + \frac{2N(He^{++})}{N(H^+)}\right]^{-1} \qquad (5)$$

In this section, $\frac{N(H^+)}{N_e}$ is estimated with the aid of relations between the intensities of Hβ, 5876 Å He I and 4686 Å He II that have been derived (Seaton 1960b) for the normal nebular case. The intensity of a recombination line is given by

$$I = N_e\, N(A^+)\, h\nu\, \alpha_{n,n'}(A)$$

where A^+ represents the recombining ion and $\alpha_{n,n'}(A)$ is the effective recombination coefficient for the transition $n \rightarrow n'$ that produces the emission line.

The relative concentrations $\frac{N(He^+)}{N(H^+)}$, $\frac{N(He^{++})}{N(H^+)}$

of singly and doubly ionized helium are found from the

relations

$$\frac{N\,(He^{+})}{N\,(H^{+})} = \frac{5876\ I\ (5876)\ \alpha_{4,2}\ (H^{\circ})}{4861\ I\ (H\beta)\ \alpha_{3\ ^{3}D,2\ ^{3}P}(He^{\circ})} \qquad (6)$$

and

$$\frac{N\,(He^{++})}{N\,(H^{+})} = \frac{4686\ I\ (4686)\ \alpha_{4,2}\ (H^{\circ})}{4861\ I\ (H\beta)\ \alpha_{4,3}\ (He^{+})} \qquad (7)$$

where $\alpha_{3\ ^{3}D,2\ ^{3}P}\ (He^{\circ}) = \frac{3}{4}\alpha_{3d,2p}\ (H^{\circ})$

and the values of $\alpha_{4,2}\ (H^{\circ})$, $\alpha_{3d,2p}\ (H^{\circ})$ and $\alpha_{4,3}\ (He^{+})$ are given by Seaton (1960b) for two cases:

Case A: the optical depths in the Lyman lines are all much less than 1;

Case B: the optical depth in the Lyman continuum is much greater than 1.

The recombination coefficients depend on the temperature, which is here taken as 10,000° K. The relative concentrations of the helium ions found from equations (6) and (7) are listed in Table 19. The mean values,

Case A: $$\overline{\frac{N\,(He^{+})}{N\,(H^{+})}} = 0.072$$

$$\overline{\frac{N(He^{++})}{N(H^{+})}} = 0.044$$

Table 19

Relative Concentrations of Helium Ions

t*	Case A†			Case B*		
	$\frac{N(He^+)}{N(H^+)}$	$\frac{N(He^{++})}{N(H^+)}$	$\frac{N(He^+)}{N(He^{++})}$	$\frac{N(He^+)}{N(H^+)}$	$\frac{N(He^{++})}{N(H^+)}$	$\frac{N(He^+)}{N(He^{++})}$
86	----	0.020	----	----	0.013	----
89	----	0.018	----	----	0.012	----
91	----	0.031	----	----	0.020	----
92	----	0.038	----	----	0.025	----
96	0.085	0.041	2.1	0.13	0.027	4.8
100	0.070	----	----	0.10	----	----
115	0.059	0.055	1.1	0.088	0.036	2.4
118	0.072	0.046	1.6	0.11	0.030	3.7
125	0.079	0.051	1.5	0.12	0.033	3.6
143	0.069	0.054	1.3	0.10	0.035	2.9
158	----	0.042	----	----	0.028	----
244	----	0.090	----	----	0.059	----

* Days since January 26, 1963. † Nebula optically thin in Lyman continuum and line radiation. * Nebula optically thick in Lyman radiation.

Case B: $\overline{\frac{N\ (He^{+})}{N\ (H^{+})}} = 0.11$

$$\overline{\frac{N\ (He^{++})}{N\ (H^{+})}} = 0.029,$$

are used to estimate $\frac{N\ (H^{+})}{N_e}$ by means of equation (5). For both Cases A and B,

$$\frac{N\ (H^{+})}{N_e} = 0.86.$$

Initially, only a thin inner layer of the shell is ionized and Case B applies. As the expansion proceeds, the ionized layer occupies an increasingly larger fraction of the shell volume and the conditions in the nebula approach those of Case A.

The Abundance of Helium

If the hydrogen in the shell is completely ionized, which corresponds to Case A, then the relative abundance of helium to hydrogen is

$$\frac{N\ (He)_{total}}{N\ (H^{+})} = \frac{N\ (He^{o}) + N\ (He^{+}) + N\ (He^{++})}{N\ (H^{+})}.$$

According to Seaton (1960a), if

$$\frac{I\ (4686)}{I\ (5876)} \geq 1.2, \qquad (8)$$

then the absorption of ionizing radiation by He^{o} is incomplete, which (for dimensions and densities typical of planetary nebulae) implies that $\frac{N\ He^{o})}{N\ (H^{+})}$ is negligible. The inequality (8) is satisfied by the observations of

I (4686) and I (5876) in Nova Herculis 1963. Therefore $\frac{N(He^{o})}{N(H^{+})}$ can be neglected, because the results of the electron density determinations which follow (e.g.: $N_e \approx 10^8$ cm^{-3} when $R \approx 10^{14}$ cm) imply that the total number of helium atoms in all ionization states per cm^2 along the radial line of sight through the shell is not less than that for an average planetary nebula ($N_e \approx 10^4$ cm^{-3}, $R \approx 10^{17}$ cm; Aller 1956) if the abundances are similar. The relative abundance of helium in the shell of Nova Herculis 1963 is thus

$$\frac{N(He)_{total}}{N(H^{+})} = 0.116 \quad \text{(Case A)}.$$

Electron Density and Temperature of the Shell

Pottasch (1959c) suggested two methods of determining N_e for the shell of a nova from the observed intensity of Hα. In general, the optical depth in Hα, $\tau(H\alpha)$, is difficult to estimate because of the effect of the velocity gradient in the shell (Sobolev 1947). However, Pottasch derived equations for N_e that are applicable in two special cases:

$$\tau(H\alpha) \gg 1$$

and

$$\tau(H\alpha) \ll 1.$$

(a) Nebula optically thick in Hα

By numerical approximation for the case where

$$V_p = 1000 \text{ km/sec}$$

and

$$R = 30 \Delta R,$$

Pottasch (1959c) found the approximation

$$I(H\alpha) = \frac{2\pi R^2 \Delta\nu_D J_o}{r^2} \qquad (9)$$

where $\Delta\nu_D$ is the Doppler width and J_o, the emergent intensity, is

$$J_o = \frac{1.04 \times 10^{-4} \sqrt{1.45 \times 10^{-14} N_e}}{1 + \sqrt{1.45 \times 10^{-14} N_e}}, \qquad (10)$$

for $$T_e = 10{,}000 \text{ °K}.$$

Equation (9) is not strongly dependent on the assumed value of $\Delta R/R$. The mass of hydrogen in an ionized shell is given by

$$M(H) = N_e \mu_H \frac{N(H^+)}{N_e} V, \qquad (11)$$

where V is the volume of the shell, μ_H is the mass of a hydrogen atom and $\frac{N(H^+)}{N_e}$ is estimated in the manner described above. During the time when the nebula is optically thick in H (α), and for some time thereafter, it is also opaque to the Lyman continuum (Pottasch 1959c). Therefore, at this stage the nebula can be regarded as consisting of

two shells, an inner H II region and an outer H I region. The value of N_e found from equation (10) pertains to the H II region. Assuming that the proton number density in the H II region equals the density of neutral hydrogen in the outer region, M (H) can be found from equation (11). Pottasch (1959c) determined M (H) in this way for several novae and found that it remained constant for a few days after maximum light and then decreased rapidly. The approximation

$$\tau(H\alpha) >> 1$$

is considered to be satisfied only during the interval of constant M (H).

The observations of Nova Herculis 1963 reported in Chapter II were made well after the date ($t \approx 4$ days) of maximum light. Therefore, according to the above discussion, the nebula probably was not optically thick in H (α) during the period of observation. However, for purposes of comparison, N_e and M (H) were calculated from equations (9), (10) and (11) for the first ten nights on which I ($H\alpha$) was measured. The results are given in Table 20. The initial values of M (H) are very high compared to those found for the case

$$\tau(H\alpha) << 1,$$

Apparently equation (9) is a poor approximation in the case of Nova Herculis 1963. However, this disparity in the values of M(H) could also be due to an overestimate of r by a factor of about three.

Table 20

Physical Properties of the Nova Shell

t*	10^{-14}R**	10^{-42}V	N_e†	N_e‡	N_e*	10^{-28}M(H)†	10^{-28}M(H)‡	T_e
	cm	cm^3	cm^{-3}	cm^{-3}	cm^{-3}	gm	gm	°K
17	1.47	3.81	1.7×10^{12}	2.73×10^{9}	1.5×10^{10}	930.	1.49	----
31	2.68	23.5	3.5×10^{10}	7.97×10^{8}	2.4×10^{9}	120.	2.68	----
47	4.06	82.9	2.0×10^{9}	3.18×10^{8}	6.8×10^{8}	24.	3.77	----
69	5.96	260.	3.2×10^{8}	1.67×10^{8}	2.2×10^{8}	12.	6.21	----
71	6.13	276.	3.0×10^{8}	1.64×10^{8}	2.0×10^{8}	12.	6.47	----
86	7.43	515.	8.9×10^{7}	1.07×10^{8}	-----	7.4	7.88	----
91	7.86	607.	6.5×10^{7}	9.47×10^{7}	-----	5.6	8.22	9100
92	7.95	637.	6.5×10^{7}	9.37×10^{7}	-----	5.9	8.54	9400
96	8.29	712.	3.4×10^{7}	7.85×10^{7}	-----	3.5	7.99	9500
115	9.94	1240.	5.5×10^{6}	4.75×10^{7}	-----	1.0	8.42	10700
118	10.2	1320.	-----	4.52×10^{7}	-----	-----	8.53	10650
125	10.8	1470.	-----	3.82×10^{7}	-----	-----	8.03	11150
140	12.1	2220.	-----	2.84×10^{7}	-----	-----	9.02	11600
143	12.4	2350.	-----	2.61×10^{7}	-----	-----	8.77	11350
146	12.6	2390.	-----	2.42×10^{7}	-----	-----	8.27	11750
158	13.7	3310.	-----	1.74×10^{7}	-----	-----	8.24	12250
218	18.8	8000.	-----	5.80×10^{6}	-----	-----	6.64	12700
244	21.1	12300.	-----	3.63×10^{6}	-----	-----	6.38	12850

*Days since January 26, 1963. **Note that $\Delta R = 0.1$ R. † Nebula optically thick in Hα

‡Nebula optically thin in both Hα and the Lyman continuum.

*Nebula optically thin in Hα and optically thick in the Lyman continuum.

(b) Nebula optically thin in Hα

When the nebula is transparent to Hα ,

$$I(H\alpha) = \frac{N_3(H^o)\, A_{3,2}\, h\nu_{3,2}\, V}{4\pi r^2}, \qquad (12)$$

where $h\nu_{3,2}$ is the energy of an Hα quantum, $A_{3,2}$ is the spontaneous radiative transition probability (4.39×10^7 sec^{-1}) and

$$N_3(H^o) \approx \frac{N(H^+)\left[A_{i,3} + A_{i,2}\left(\frac{C_{2,3}}{C_{2,1} + C_{2,i} + C_{2,3}}\right)\right]}{A_{3,2}\left(\frac{C_{2,1} + C_{2,i}}{C_{2,1} + C_{2,i} + C_{2,3}}\right)} \qquad (13)$$

is the number density of hydrogen atoms in the third level (Pottasch 1959c). With the exception of $A_{3,2}$, the rate coefficients in equation (13) are temperature-dependent and are expressed in units of N_e sec^{-1}. They are tabulated by Jefferies and Pottasch (1959) and are defined as follows:

$A_{i,2}$ and $A_{i,3}$ - rates of spontaneous recombination on the second and third levels, respectively;

$C_{2,1}$ - rate of collisional de-excitation of the second level;

$C_{2,3}$ - rate of collisional excitation from the second to the third level;

$C_{2,i}$ - rate of collisional ionization from the second level.

The function

$$f(T_e) = \frac{N_e N(H^+)}{N_3(H^o)}$$

was calculated for the range

$$9000\ ^\circ K \leq T_e \leq 14{,}000\ ^\circ K,$$

using equation (13) and the rate coefficients given by Jefferies and Pottasch (1959); it is shown in Figure 8.

From the above discussion, it is seen that I (Hα) depends on both N_e and T_e. Another relation between these two variables can be written in terms of the intensities of the [O III] lines:

$$\mathcal{R}(O^{++}) = \frac{I\ (4363)}{I\ (4959 + 5007)}$$

$$= 13.1 \times 10^{-14{,}300\ T_e^{-1}} \left[\frac{1.012 + 2300\ T_e^{\frac{1}{2}}\ N_e^{-1}}{1.01 + 2.70 \times 10^5\ T_e^{\frac{1}{2}}\ N_e^{-1}}\right] \quad (14)$$

(Aller 1956). Equation (14) is the general expression for $\mathcal{R}(O^{++})$. Approximations to $\mathcal{R}(O^{++})$ have been derived for the electron densities typical of planetary and diffuse nebulae (Aller 1956; Seaton 1960b). In the limit of high densities,

Ratio of the product of the electron and proton densities to the population of the third level of neutral hydrogen, as a function of electron temperature.

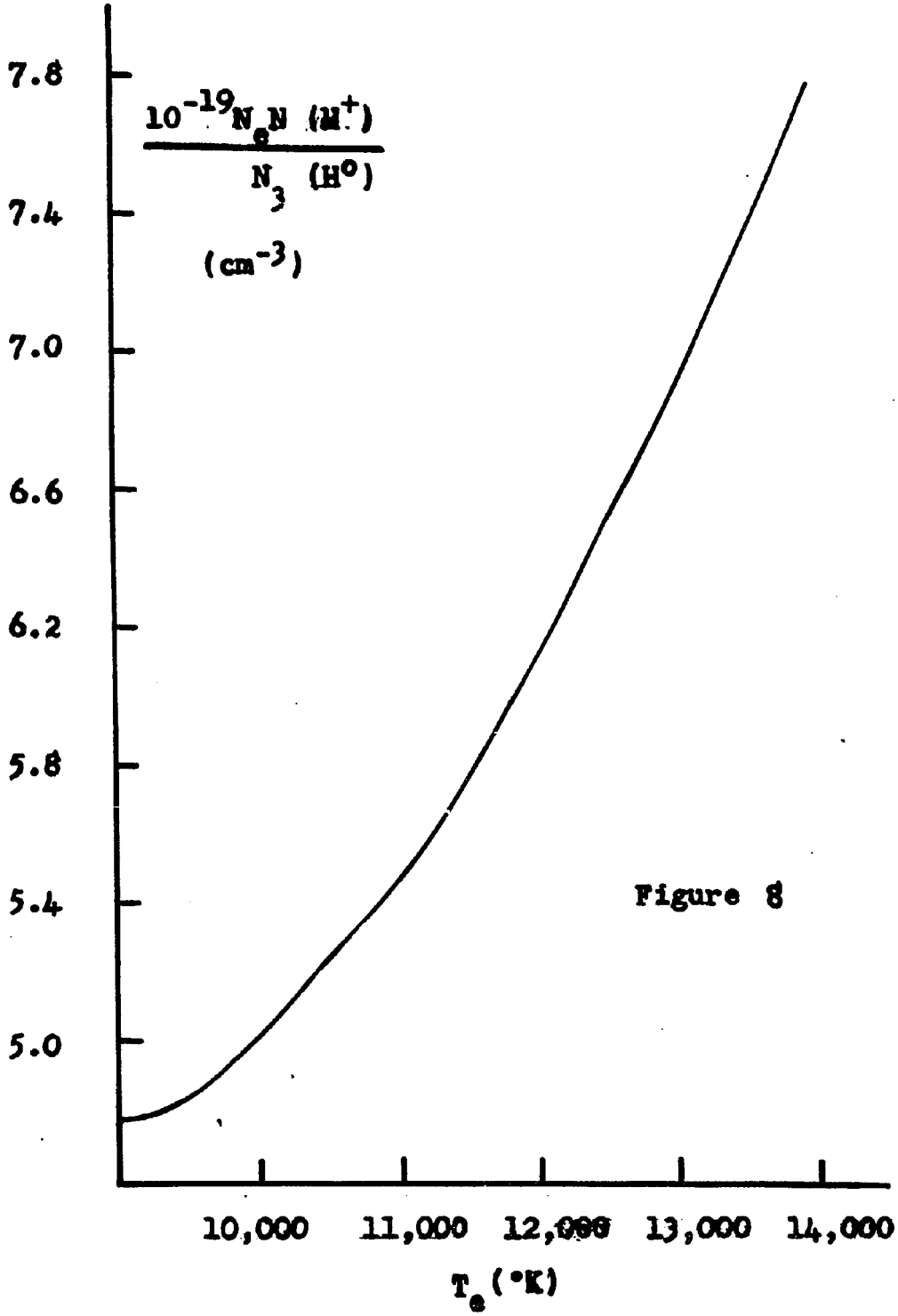


Figure 8

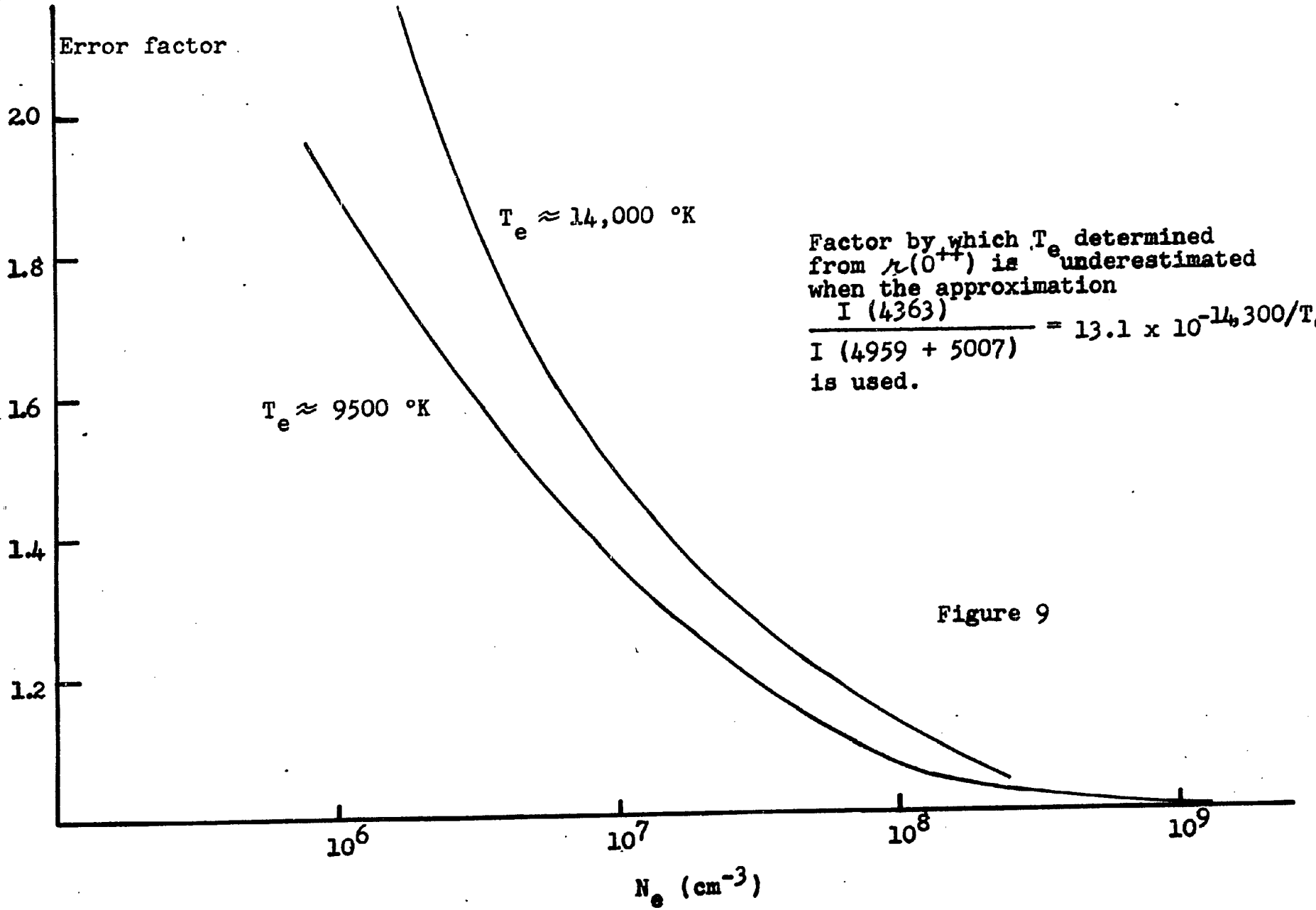
$$\mathcal{R}(O^{++}) \approx 13.1 \times 10^{-14,300\ T_e^{-1}} \qquad (15)$$

Relations similar to equation (15) have been used to derive T_e for the shells of novae (Payne-Gaposchkin and Gaposchkin 1942; McLaughlin 1960). However, this method leads to the misleading result that T_e decreases with time, because the effect of N_e on $\mathcal{R}(O^{++})$ really cannot be neglected, as is shown by Figure 9. The range of N_e in the figure corresponds to that found in novae shells by Pottasch (1959c). It is clear that as a shell expands and N_e decreases, equation (15) underestimates T_e by increasingly large factors.

N_e and T_e were found from the measured values of I (Hα), I (4363) and I (4959 + 5007) for Nova Herculis 1963, using equations (12) and (14). The results are given in Table 20. For $t < 91$ days, $\mathcal{R}(O^{++})$ was not measured, and N_e was calculated from I (Hα) and equation (12), on the assumption that

$$T_e = 10{,}000^\circ \text{ K}.$$

It is seen from Figure 8 that the values of N_e derived from I (Hα) are not very sensitive to the assumed T_e for temperatures less than 10,000° K. $\mathcal{R}(O^{++})$ also was not obtained on $t = 140$, 146 and 244 days. For these three dates, T_e was adopted from a smooth curve passed through the values calculated for $t \geq 91$ days (Figure 10).

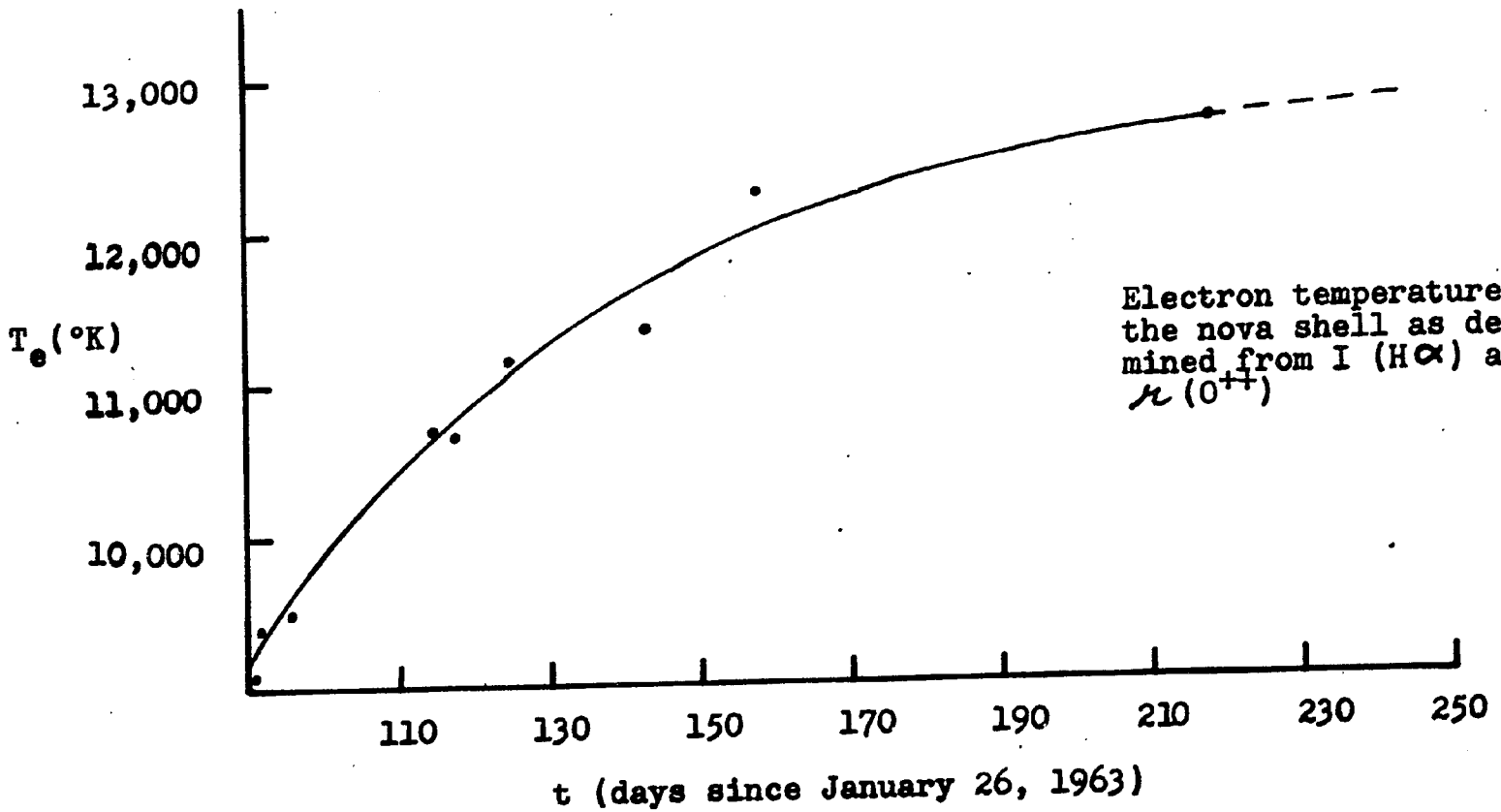


Factor by which T_e determined from $\mathcal{R}(O^{++})$ is underestimated when the approximation

$$\frac{I\,(4363)}{I\,(4959 + 5007)} = 13.1 \times 10^{-14{,}300/T_e}$$

is used.

Figure 9



Electron temperature of the nova shell as determined from I (Hα) and $\mathcal{R}$ (O^{++})

Figure 10

The increase of T_e with time (Figure 10), if real, corresponds to an increase in the thermal energy of the nebula by a factor of 1.4 during the interval from t = 91 days to t = 244 days.

The electron temperature of a gaseous nebula is determined by the balance between the amount of ionizing radiation absorbed by the gas and the energy that it radiates, chiefly in the emission lines. Thus, since the amount of ionizing radiation that is absorbed remains constant (the shell is optically thin in the Lyman continuum), the increase in T_e can be regarded qualitatively as being due to the decreasing emission rate of the expanding shell. Most recently, Zanstra (1955), Seaton (1960b) and Daub (1963) have studied the energy balance problem for a gaseous nebula in a steady state, and have derived relations between T_e and the stellar temperature, T_s. However, the nonequilibrium conditions in the shell of a nova, including

(a) the expansion of the gas,

(b) the changing intensity and spectral distribution of the radiation emitted by the exciting star,

and (c) the changing relative concentrations of the ions that are important emitters,

make it unlikely that a steady state analysis can be applied to the present case. In fact, if the observed values of T_e, T_s* and $\frac{N(O^{++})}{N(H^+)}$* for Nova Herculis 1963 are substituted

---

* Discussed in subsequent sections.

in the energy balance equation

$$\phi_{kT_e} + \frac{C_1 \exp(-\Delta E/kT_e)\, N(O^{++})}{\alpha(H^o)\, T_e^{\frac{1}{2}}\, N(H^+)} = \psi_{kT_s}, \quad (16)$$

where N_1+N_2 is assumed to be the only significant forbidden emission (Seaton 1960b), it is found that the equality does not hold (Table 21). (In equation (18), ϕ and ψ are functions of T_e and T_s, respectively, C_1 is a constant, ΔE is the excitation potential of the of the $^1D_2$ level of O^{++}, and $\alpha(H^o)$ is the recombination coefficient for hydrogen.)

Table 21

Ratios of Observed to Theoretical Stellar Temperatures

t^*	T_s(observed)/T_s (eqn. (18))
91	0.1
92	0.1
96	0.2
115	0.4
118	0.3
125	0.4
143	0.5
158	0.5
244	1.3

*Days since January 26, 1963.

An apparent increase in T_e would also be observed if N_e were systematically underestimated, because $\alpha(O^{++})$ is

more and more sensitive to N_e as N_e decreases (Figure 9). As an extreme case, let us suppose that T_e were actually constant at about 9000° K. Then it follows from Figure 9 that the apparent increase of 40% in T_e could be attributed to a systematic underestimate of N_e by a factor of about 20. So serious an underestimate is unlikely to arise wholly from an error in the adopted distance to the nova, since N_e is directly proportional to r when the shell is optically thin in Hα. However, if condensations are present in the nebula, the derived N_e, that is, the root-mean-square value, is an underestimate (Seaton and Osterbrock 1957).

For example, if the expanding nebula consisted of a number of condensations of equal electron density N_e', then the derived N_e would be

$$N_e = N_e' \sqrt{\frac{V'}{V}}$$

where V' is the total volume of the condensations. If,

$$\frac{N_e'}{N_e} = 20,$$

then

$$V' = \frac{1}{400} V.$$

In fact, considerable structure has been observed in the nova shells that have been photographed or examined visually (Pease 1920, Jones 1931, Kuiper 1940 and 1941, Baade 1942, van de Hulst 1951). Probably both the changing energy balance and the presence of condensations are responsible for the observed increase of T_e. A further possibility, suggested by Oort (1946), is that the shell is heated by friction with the interstellar gas.

Mass of Hydrogen in the Shell; Thickness of the H II Region

The mass of hydrogen in the shell was computed, using the derived values of N_e (for $\tau(H\alpha) << 1$) and equation (11). The results are given in Table 20. At first, M (H) increases with time because N_e has been underestimated. This is due to the fact that the shell is still partly neutral, and thus too large a value of V has been used in equation (12). M (H) is roughly constant for $t \geq 86$ days. It is concluded that the shell became fully ionized and hence transparent to the Lyman continuum by $t \approx 86$ days.

In order to compute the electron density in the H II region for $t < 86$ days, a simple model is assumed. The shell is divided into an H I region, having thickness ΔR_I and hydrogen number density N (H^o), and an H II region having thickness ΔR_{II} and proton density N (H^+). Obviously

$$\Delta R = \Delta R_I + \Delta R_{II} .$$

Further, it is assumed that

$$N(H^o) = N(H^+) .$$

If the true mass of hydrogen in the shell is the average value of M (H) for $t \geq 86^d$ (i.e.: 8.07×10^{28} gm), then the electron density in the H II region is

$$N_e(II) = N_e \left(\frac{8.07 \times 10^{28}}{M(H)} \right) , \qquad (17)$$

where N_e and M (H) are quantities determined on the assumption that the shell is fully ionized. N_e (II) is referred

to as the electron density for the case where the shell is optically thin to H α but optically thick to the Lyman continuum; it was computed from equation (17) and is listed in Table 20 .

The thickness of the ionized region is given by

$$\Delta R_{II} \approx \Delta R \left(\frac{N_e}{N_e\ (II)} \right)^2$$

or

$$\Delta R_{II} \approx \Delta R \left(\frac{M\ (H)}{8.07 \times 10^{28}} \right)^2 . \qquad (18)$$

ΔR_{II} was computed from equation (18). The results are given in the following table.

Table 22

Thicknesses of the H II and H I Regions

t*	ΔR_{II}	ΔR_I
17	5.0×10^{11} cm	1.4×10^{13} cm
31	2.9×10^{12}	2.4×10^{13}
47	8.8×10^{12}	3.2×10^{13}
69	3.5×10^{13}	2.4×10^{13}
71	3.9×10^{13}	2.2×10^{13}
$\gtrsim 86$	ΔR	0

* Days since January 26, 1963.

Relative Concentration of Doubly Ionized Oxygen

The relative concentration

$$\frac{N\ (O^{++})}{N\ (H^{+})}$$

of doubly ionized oxygen is estimated from the equation

$$\frac{N\ (O^{++})}{N\ (H^{+})} = \frac{4995}{4861}\ \frac{I\ (4959 + 5007)}{I\ (H\alpha)}\ \frac{N_e\ S\alpha_{4,2}\ (H^{o})}{(A_{4959} + A_{5007})P} \qquad (19)$$

(after Seaton 1960b), where A_{4959} and A_{5007} are the transition probabilities of the nebular lines of [O III] and S and P are functions of N_e and T_e:

$$P = 5.4 \times 10^{-3} \exp(-\Delta E/kT_e) \cdot X \left[1 + 0.12\epsilon + 4.1 \times 10^{-4} X(1 + 0.11\epsilon)\right],$$

$$S \approx P + 1 + 0.01\ X\ (1 + 0.05\epsilon) + 3.9 \times 10^{-6}\ X^2\ (1 + 0.1\epsilon);$$

$$X = 10^{-2}\ N_e\ T_e^{-\frac{1}{2}}$$

and

$$\epsilon = \exp\ (-3.30 \times 10^{4}\ T_e^{-1}).$$

The results (Table 23) are uncertain because the effects of collisional processes on the intensity of $H\beta$ are not taken into account.

Table 23

Relative Concentrations of O^{++} in the Shell

t*	$\frac{10^3 N(O^{++})}{N(H^+)}$
91	5.6
92	5.0
96	4.1
115	2.0
118	2.2
125	1.8
143	1.6
158	1.2
218	1.0
244	0.66

* Days since January 26, 1963.

Table 24

Stellar Temperatures and Radii

t*	T_s °K	R_s solar radii
86	105,000	0.97
89	105,000	0.99
91	120,000	0.76
92	125,000	0.69
96	130,000	0.61
115	150,000	0.38
118	140,000	0.43
125	145,000	0.35
143	150,000	0.28
158	135,000	0.27
244	195,000	0.08

$R_\odot = 6.96 \times 10^{10}$ cm.

Stellar Temperature and Radius

Again neglecting the effects of collisional processes, the temperature, T_s, and radius, R_s, of the star were computed by the method of Zanstra (1931), which assumes complete absorption of the ionizing radiation. T_s and R_s were found from simultaneous solution of

$$I(H\beta) = \left(\frac{2\pi I_H^3}{h^2c^2}\right)\nu(H\beta)\left(\frac{R_s}{r}\right)^2 \frac{\alpha_{4,2}(H^o)}{\sum_{n>1}(\alpha_n(H^o))} \frac{F_1(y)}{y^3} \quad (20)$$

and

$$I(4686) = \left(\frac{2\pi I_H^3}{h^2c^2}\right)\nu(4686)\left(\frac{R_s}{r}\right)^2 \frac{\alpha_{4,3}(He^+)}{\sum_{n>1}(\alpha_n(He^+)} \frac{F_1(4y)}{y^3} \quad (21)$$

(Seaton 1960b), where I_H is the ionization potential of hydrogen and

$$y = \frac{I_H}{kT_s}$$

The function $F_1(y)$ is tabulated by Zanstra. The results show that as the radius of the star decreased, the stellar temperature increased; they are presented in Table 24.

The Balmer Decrement

The Balmer decrement is given in Table 25. Due to the effect of blending on the other hydrogen lines (cf: Chapter II), only the ratio

$$d(\alpha) = \frac{I(H\alpha)}{I(H\beta)}$$

is considered to be accurately determined. The variation of this ratio with time (Figure 11) is in qualitative agreement with the theory of Kogure (1961). He suggested that $d(\alpha)$ should rise during the early history of the nova, when the radiation field in the shell resembles that found in the envelope of a Be star, but that when the dilution factor

$$W = \frac{R_s^2}{4R^2}$$

falls below a critical value of about 10^{-3}, $d(\alpha)$ should decrease and approach the value (2.5) that is characteristic of a nebular recombination spectrum. However, the observed values of $d(\alpha)$ do not exceed 6, whereas much larger peak values, e.g.:

$$d(\alpha)_{max} \approx 60$$

for $T_e = 26{,}300\ ^\circ K$

and

$$d(\alpha)_{max} \approx 40$$

for $T_e = 15{,}800\ ^\circ K$,

Table 25

Balmer Decrements†

t*	Hα	Hβ	Hγ	Hδ‡	Hε‡	Hζ‡
17	2.79	1	.29	.16	.13	.057
20	----	1	.31	.20	.17	.057
31	3.27	1	.46	.27	.18	.091
47	5.78	1	.50	.44	.26	.083
69	4.37	1	.61	.59	.34	.10
71	4.92	1	----	----	----	----
86	3.95	1	----	----	----	----
91	3.90	1	.52	.56	.24	.24
92	4.23	1	.58	.63	.23	.19
96	3.66	1	.51	.61	.22	.22
115	3.35	1	.47	.66	----	----
118	3.24	1	.47	.48	----	----
125	3.30	1	.53	.63	.21	----
143	3.26	1	.56	.51	.28	----
146	2.88	1	----	----	----	----
158	2.87	1	.62	----	----	----
218	2.49	1	.45	----	----	----
244	1.61	1	----	----	----	----

*Days since January 26, 1963. †Corrected for interstellar reddening on the assumption that $A_V = 0^m.2$. ‡Includes emission of other atoms (cf: Chapter II).

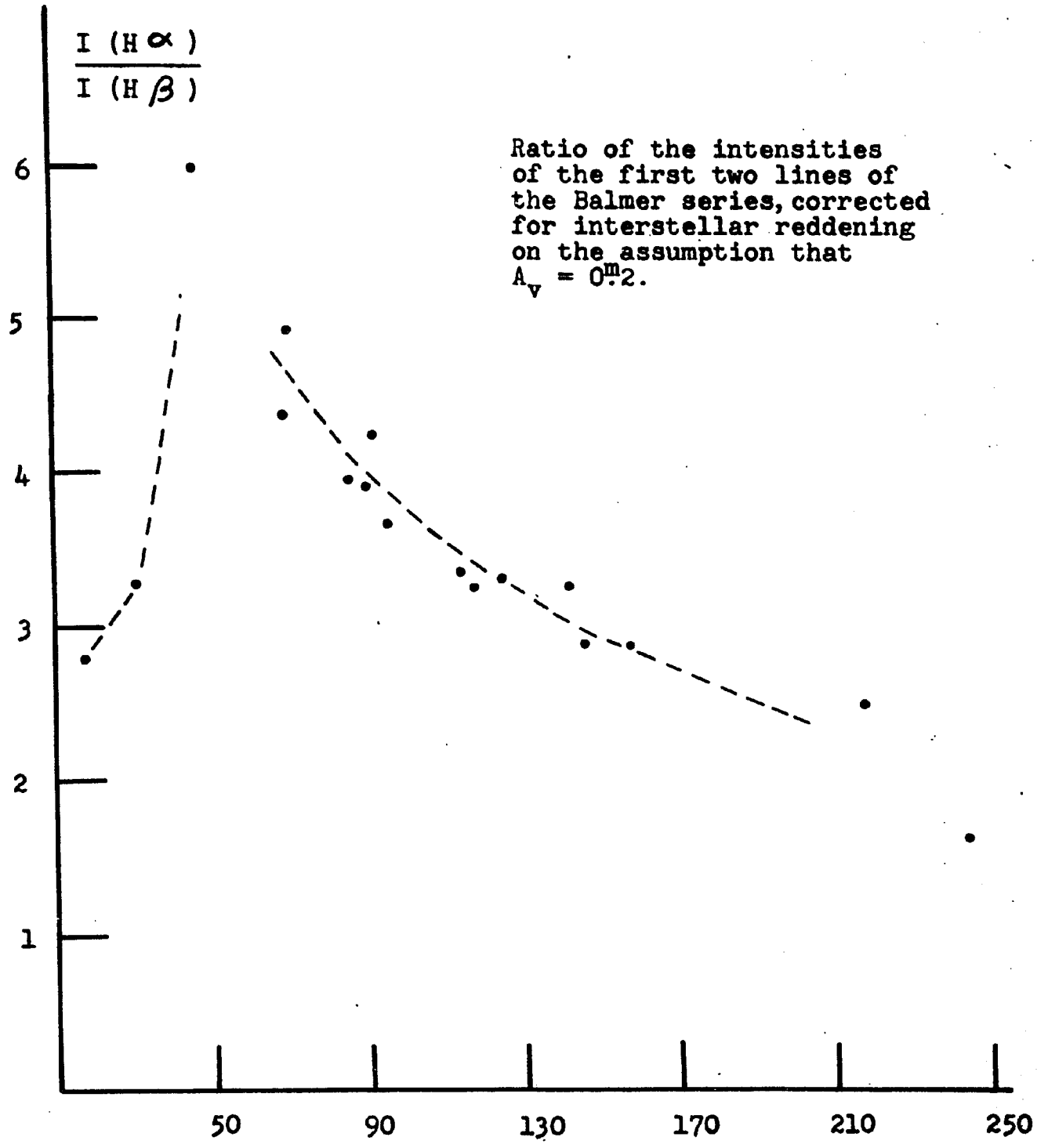

I (Hα)
I (Hβ)
6
5
4
3
2
1
50
90
130
170
210
250
t (days since January 26, 1963)
Ratio of the intensities of the first two lines of the Balmer series, corrected for interstellar reddening on the assumption that $A_v = 0^m.2$.

Figure 11

are predicted by Kogure. Meinel (1963) made a large number of observations of d (α) in Nova Herculis 1960; his data define the peak value very well and show that it was less than 7. The discrepancy may arise from the fact that Kogure did not take into account two effects that can have a strong influence on the Balmer decrement: collisional transitions (Chamberlain 1953) and the velocity gradient in the shell (Sobolev 1947). W is not known for t $\lesssim$ 86 days, because R_s is unknown and may have been rapidly decreasing. For t $\gtrsim$ 86 days, W $< 10^{-8}$.

The last observed value of d (α), 1.6 on t = 244 days, is much lower than the recombination value of 2.5. However, the signal-to-noise ratios for both Hα and Hβ were low on this date and also the systematic transparency variation that may have occurred (cf: Chapter II) would have had the effect of causing the intensities of lines in the red part of the spectrum to be underestimated.

Intensity of the Continuum

The measurements of the intensity of the continuous spectrum that were obtained in the present investigation are quite poor, due to the reasons discussed in Chapter II. Therefore, no attempt is made to interpret the shape of the continuum. However, the measured absolute level of the continuum in the visual region is certainly accurate to within a factor of two.

Miss Seitter (1963) studied the relative intensity distribu-

tion in the continuum of Nova Herculis 1963, as determined from objective prism spectra. She found that the shape of the continuum remained essentially the same while the nova faded over a period of several months. Further, it was very similar to the shape of a theoretical nebular continuum calculated by the method of Seaton (1960b) for the case where

$$N_e = 5 \times 10^4 \text{ cm}^{-3}$$

and

$$T_e = 20{,}000 \text{ °K.}$$

These values seem unlikely to be correct for two reasons:

(a) constancy of N_e and T_e, in the case of fading nebular emission, implies a decrease in the radiating volume;

(b) the values of N_e determined by the writer from absolute measurements of the emission lines are much greater than that suggested by Miss Seitter.

In fact, the measurements of the <u>absolute</u> intensity of the continuum (Chapter II) indicate that the agreement of the relative energy distribution with that predicted for

$$N_e = 5 \times 10^4 \text{ cm}^{-3}$$

and

$$T_e = 20{,}000 \text{ °K}$$

is fortuitous. As an example, the absolute intensity of the continuum near $H\beta$, as measured at t = 31 days, can be used

together with the above values of N_e and T_e, to determine the radiating volume. According to Seaton (1960b), the intensity in a nebular continuum, in ergs cm^{-3} sec^{-1}, can be expressed in the form

$$d\mathcal{E} = \sum \left(N\,(A^+)\, N_e \gamma \right) d\,(h\nu)$$

where the function $\gamma\,(A^+, T_e)$, tabulated by Seaton, is expressed in the units of a recombination coefficient, i.e.: cm^3 sec^{-1}, and the summation is performed over the different ions A^+. The measured continuum intensity is

$$I_\nu = \frac{V}{4\pi r^2} \frac{d\mathcal{E}}{d\nu} .$$

The detailed expression is then

$$V = \frac{4\pi r^2 I}{h N_e N(H^+)} \left[\gamma(H^o) + \gamma(2q) + \gamma(He^o) \frac{N\,(He^+)}{N\,(H^+)} + \gamma(He^+) \frac{N\,(He^{++})}{N\,(H^+)} \right]^{-1}$$

where the coefficient pertaining to the two-quantum emission process is

$$\gamma\,(2q) = \frac{\gamma_o\,(2q)}{1 + 0.6 \times 10^{-4} N_e}$$

and $\gamma_o\,(2q)$ is tabulated as a function of T_e by Seaton (1960b). If

$$N\,(H^+) \approx N_e = 5 \times 10^4 \text{ cm}^{-3},$$

$$T_e = 20{,}000\ ^\circ K,$$

$$\lambda \approx 4860\ \text{Å},$$

$$I = 4 \times 10^{-22}\ \text{erg cm}^{-2}\ \text{sec}^{-1},$$

$$\frac{N(He^+)}{N(H^+)} \approx 10^{-1},$$

and

$$\frac{N(He^{++})}{N(H^+)} \approx 4 \times 10^{-2}$$

then

$$V \approx 7 \times 10^{52}\ \text{cm}^3.$$

This volume corresponds to a sphere of radius

$$R \approx 2.5 \times 10^{17}\ \text{cm},$$

which is about 10^3 times greater than the product $\bar{V}_p t$ for t = 31 days. The value of R found by this method is insensitive to the assumed distance, because

$$R \sim r^{2/3}.$$

Perhaps the problem of the continuous spectrum of the nova can be resolved by taking into account the contribution of the stellar photosphere. Only a very uncertain estimate can be made for this quantity, since R_s and T_s were not found for the period during which the continuum measurements were made and they are both rapidly changing functions of time. As an

example, the intensity of black body radiation expected from a star having

$$R_s = 5\ R_\odot \approx 3.5 \times 10^{11}\ \text{cm}$$

$$T_s = 50{,}000\ ^\circ\text{K}$$

and located at the distance, r, of the nova is calculated from the equation

$$I_\nu = \frac{4\pi R_s^2}{4\pi r^2} \quad \frac{2\pi h\nu^3}{c^2(\exp(h\nu/kT) - 1)} .$$

For 4860 Å,

$$I_\nu \approx 10^{-22}\ \text{erg cm}^{-2}\ \text{sec.}$$

Comparison of this figure with the observed intensity of 4×10^{-22} erg cm^{-2} sec^{-1} shows that the contribution of the stellar continuum cannot be neglected. The visible radiation of the star is certainly not absorbed in the shell, since the shell is optically thin in H α .

CHAPTER IV

DISCUSSION

Effects of an Error in the Adopted Distance or Visual Absorption

The derived physical parameters of Nova Herculis 1963, discussed in Chapter III, may contain systematic errors resulting from the possible use of an incorrect value of the distance modulus as determined at maximum light, $M_{V_o} - m_{V_o}$. Systematic errors will also be present if an incorrect value of the visual interstellar absorption, A_V, has been adopted. In this section, the errors introduced by incorrect values of $M_{V_o} - m_{V_o}$ and A_V are considered for two simple cases:

adopted $M_{V_o} - m_{V_o}$ correct, but A_V wrong;

adopted $M_{V_o} - m_{V_o}$ wrong, but A_V correct.

If the adopted value

$$M_{V_o} - m_{V_o} = -10.6$$

is correct, then an error in the assumed value of A_V causes (a) an error in the distance determined from equation (1), and (b) systematic errors in quantities determined from emission line intensities or intensity ratios.

As an example, the values of N_e and T_e for t = 91 days

were calculated using equations (12) and (14), for values of A_v between 0 and $0^m.7$, inclusive. Both N_e and T_e were found to be linearly dependent on A_v, according to the relations

$$T_e\ (t = 91) = (8950 + 570\ A_v)\ °K$$

and

$$N_e\ (t = 91) = (9.67 - 0.96\ A_v) \times 10^7\ cm^{-3}\ .$$

Thus, T_e increases with A_v, and N_e decreases.

In the range of A_v considered, the values of $\frac{N\ (O^{++})}{N\ (H^+)}$, T_s and R_s corresponding to a given date are constant within a few percent, as are the average values of $\frac{N\ (He^{++})}{N\ (H^+)}$ and $\frac{N\ (H^+)}{N_e}$. The average value of $\frac{N\ (He^+)}{N\ (H^+)}$ varies from 0.077 for $A_v = 0.0$ to 0.066 for $A_v = 0.7$.

An error in the adopted value of $(M_{v_o} - m_{v_o})$ leads to an error in the distance. In order to evaluate this effect, values of N_e and T_e for t = 91 days were computed from equations (12) and (14) for assumed distances in the range of 400 to 2400 parsecs. The adopted value of the visual absorption,

$$A_v = 0^m.2,$$

was assumed to be correct. As expected, N_e was found to be proportional to r, since its dependence on T_e is very weak.

The results are presented in the following table.

Table 26

Dependence of N_e and T_e on the Assumed Distance*

r	10^{-7} N_e	T_e
pc	cm-3	°K
400	3.24	10,100
800	6.33	9350
1200	9.47	9100
2400	18.9	8800

* For t = 91 days and $A_v = 0^m.2$.

The computed values of $\frac{N(He^+)}{N(H^+)}$, $\frac{N(He^{++})}{N(H^+)}$, $\frac{N(H^+)}{N_e}$, and T_s are not sensitive to an error in the distance, because the dependence of these quantities on T_e is weak. Since T_s is not affected by an error in r, it is clear from equations (20) and (21) that R_s is proportional to r. Further, $\frac{N(O^{++})}{N(H^+)}$, computed from equation (19) using the data in Table 26, is also found to be a linear function of r over the range 400 pc $\leq$ r $\leq$ 2400 pc. The following relation was found for t = 91 days:

$$\frac{N(O^{++})}{N(H^+)} = 8.56 \times 10^{-4} + 5.56 \times 10^{-6} r .$$

From consideration of the errors that can arise from an incorrect assumed value of A_v or $M_{v_o} - m_{v_o}$, it is clear that the physical parameters presented in Chapter III must be regarded as largely illustrative in nature, giving general orders of magnitude.

Comparison with Previous Work

The observed intensities of the emission lines in Nova Herculis 1963, assuming a distance of 1200 parsecs and interstellar reddening corresponding to a visual absorption of $0^m.2$, are similar to those found in previous novae. In Table 27, the maximum observed intensity of 4959 Å + 5007 Å [O III] for Nova Herculis 1963 is compared with the values reported for six novae by McLaughlin (1960).

Table 27

Maximum Integrated Emission Rates in $N_1 + N_2$ for 7 Novae

Nova	$4\pi r^2$ I (4959 + 5007)
	erg sec^{-1}
GK Persei 1901	4.9×10^{35}*
V603 Aquilae 1918	9.8×10^{36}*
V476 Cygni 1920	1.1×10^{36}*
RR Pictoris 1925	2.2×10^{35}*
DQ Herculis 1934	1.8×10^{35}*
DK Lacertae 1950	3.2×10^{34}
Herculis 1963	5.9×10^{36}

* Based on data of Payne-Gaposchkin and Gaposchkin (1942) but recalculated using improved distance estimates.

The values of N_e and T_e found in the present study are similar to those found for five novae by Pottasch (1959c). He used emission line intensities, published by Payne-Gaposchkin and Gaposchkin (1942) and Popper (1940) that were estimated from spectrograms. No systematic variation of T_e with time is evident in Pottasch's results. However, the intensity measurements used by him are uncertain by factors of two. In fact, in the case of four novae, $H\alpha$ intensities were not available, and Pottasch assumed that

$$I(H\alpha) = 3 \cdot I(H\beta).$$

As discussed in Chapter III, the decrease of T_e with time found by some workers is very likely due to the failure to take into account the effect of N_e on the intensity ratio $\mathcal{R}(O^{++})$. This is also no doubt why the electron temperatures of novae determined by approximations of the form

$$\mathcal{R}(O^{++}) = 13.1 \times 10^{-14300\, T_e^{-1}}$$

do not exceed about 10,000° K (McLaughlin 1960), whereas values of T_e as high as 14,100° K (Pottasch 1959c) and 12,850° K (present study) are found from the complete expression for $\mathcal{R}(O^{++})$, equation (14).

The computed mass of hydrogen in the shell, 8 x 10^{28} grams, can be compared with the range of M (H) among other novae, namely 10^{27} to 10^{29} grams (McLaughlin 1960).

Pottasch (1959d) determined $\frac{N\ (He)_{total}}{N\ (H^+)}$ for the shells of five novae, using emission line intensities determined from spectrograms. The values ranged from .062 to 0.32, with a mean of 0.19. The present result is 0.12.

The largest value of $\frac{N\ (O^{++})}{N\ (H^+)}$ determined in the present study is 5.6 x 10^{-3}. This can be regarded as a lower limit to the relative abundance, $\frac{N\ (O)_{total}}{N\ (H)}$, of oxygen to hydrogen. Pottasch (1959c) found that the mean value of $\frac{N\ (O)_{total}}{N\ (H)}$ among five novae was 3.6 x 10^{-3}; the range was from 1.5 x 10^{-3} to 2.2 x 10^{-2}.

The stellar photoionization temperatures and radii determined for Nova Herculis 1963 (Table 24) resemble those found for five novae by Pottasch (1959d) He considered that T_s decreases with time. This conclusion was largely based on a comparison of photoionization temperatures for the nebular stage (typically 140,000 °K) with the stellar temperatures of about 60,000 °K that characterize novae near minimum light (McLaughlin 1943 and 1953). However, McLaughlin also found, that the decrease of T_s to its post-nova value begins during the final stages of the decline toward minimum light. Obviously, at some point during the

nova phenomenon, T_s must increase. Thus the present result, namely an increase of T_s during the first five months of the nebular stage, appears to be reasonable. Photospheric radii determined from the absolute magnitude and an assumed effective temperature (summarized by McLaughlin 1960) are typically 10^2 $R_\odot$ at maximum light (effective temperature about 9000°K) and $< 10^{-1}$ $R_\odot$ at minimum light (effective temperature about 60,000° K). Larsson-Leander (1954) found $R = 1.7$ $R_\odot$ for Nova DK Lacertae 1950 in the early nebular stage.

Conclusion

Intensities (in erg/cm^{2}sec) of emission lines in the spectrum of Nova Herculis 1963 have been determined photoelectrically for the first time, and are presented in Chapter II. They are probably more accurate than any previously published emission line strengths in novae.

The physical parameters T_e, T_s, N_e, R_s, $\frac{N(H^+)}{N_e}$, $\frac{N(He^+)}{N(H^+)}$, $\frac{N(He^{++})}{N(H^+)}$, $\frac{N(He)}{N(H)}$, $\frac{N(O^{++})}{N(H^+)}$, ΔR (H II), ΔR (H I), and M (H) are derived in Chapter III on the assumption that $A_v = 0^m.2$ and $r = 1200$ parsecs. Some of the parameters will contain large systematic errors if these adopted values are wrong, but the trends reported (e.g.: the increases of T_e and T_s with time) should still be correct.

BIBLIOGRAPHY

Ahlmark, L.F., and Clemert, K.-A. 1964, Ark. f. Astron., 3, 333.

Aller, L.H. 1956, Gaseous Nebulae (New York, N.Y.: John Wiley and Sons).

Aller, L.H., and White, M.L. 1949, A.J., 54, 181.

Andrillat, Y., and Bloch, M. 1963, C.R., 256, 3961.

Anonymous 1963, Sky and Telescope, 25, 207.

Arend, S. 1963, I.A.U. Circ., No. 1824.

Arp, H.C. 1956, A.J., 61, 15.

Baade, W. 1942, Pub. A.S.P., 54, 244.

Barlier, F. 1963, I.A.U. Circ., No. 1824.

Baschek, B. 1964, Pub. A.S.P., 76, 22.

Bashkin, S., and Meinel, A.B. 1964, Ap. J., 139, 413.

Batten, A.H., Richardson, E.H., and Wright, K.O. 1963, A.J., 68, 272.

Beer, A. 1936, M.N., 96, 236.

Bertiau, F.C. 1962, Trans. I.A.U., 11 B, 366.

Bloch, M. 1950, Ann. d'ap., 13, 390.

Bloch, M., and Chalonge, D. 1963, C.R., 256, 4162.

Boyce, P.B. 1963, Thesis, U. of Michigan.

Breckenridge, J.B. 1964, Pub. A.S.P., 76, 110.

Burgers, J.M. 1946, Proc. Netherlands Acad. Sci., 49, 588.

Buscombe, W., and de Vaucouleurs, G. 1955, Observatory, 75, 170.

Cannon, A.J. 1920, Harvard Obs. Ann., 81, 179.

Chamberlain, J.W. 1953, Ap.J., 117, 387.

Clarke, D. 1964, Observatory, 84, 28.

Code, A.D. 1960, Stellar Atmospheres, ed. J.L. Greenstein (Chicago, Ill.: U. of Chicago Press), p. 50.

Copson, E.T. 1950, M.N., 110, 239.

Crawford, J.A., and Kraft, R.P. 1956, Ap.J., 123, 44.

Dahlgren, E. 1963, I.A.U. Circ., No. 1817.

Daub, C.T. 1963, Ap.J., 137, 184.

Engver, N. 1963, I.A.U. Circ., No. 1817.

Gaposchkin, S.I. 1963, Harvard Announcement Card, No. 1587.

Garstang, R.H. 1951, M.N., 111, 115.

Haddock, F.T., Howard, W.E.,III, Malville, J.M., and Seling, T.V. 1963, Pub. A.S.P., 75, 456.

Hardie, R.H. 1962, Astronomical Techniques, ed. W.A. Hiltner (Chicago, Ill.: U. of Chicago Press), p. 178.

Hazlehurst, J. 1962, Adv. Astron. Astrophys., 1, 1.

Helt, B., and Gyldenkerne, K. 1963, Harvard Announcement Card, No. 1587.

Hogg, D.E. 1963, Reports of Observatories, A.J., 68, 664.

Hubble, E.P. 1929, Ap.J., 69, 143.

van de Hulst, H.C. 1951, Problems of Cosmical Aerodynamics, ed. J.M. Burgers and H.C. van de Hulst (Dayton, Ohio: Central Air Documents Office), p. 116.

Iwanowska, W., and Burnicki, A. 1962, Bull. Astron. Obs. N. Copernicus U. (Torun), No. 32.

Jefferies, J., and Pottasch, S. 1959, Ann. d'ap., 22, 310.

Johnson, H.L., and Morgan, W.W. 1953, Ap.J., 117, 313.

Jones, H.S. 1931, Cape Obs. Ann., 10, Part 9.

Kogure, T. 1961, Pub. Astron. Soc. Japan, 13, 335.

Kraft, R.P. 1958, Ap.J., 127, 625.

———. 1961, Science, 134, 1433.

———. 1962, Ap.J., 135, 408.

———. 1964, ibid., 139, 457.

Kraft, R.P., Mathews, J., and Greenstein, J.L. 1962, Ap.J., 136, 312.

Kuiper, G.P. 1940, Ap.J., 86, 102.

———. 1941, Pub. A.S.P., 53, 330.

Larsson-Leander, G. 1954, Stockholm Obs. Ann., 18, No. 3.

———. 1963, I.A.U. Circ., No. 1818.

Liller, M.H. 1963, Harvard Announcement Card, No. 1591.

Luyten, W.J. 1963, Harvard Announcement Card, No. 1593.

McLaughlin, D.B. 1937, Pub. Obs. U. of Michigan, 6, 107.

———. 1942, Pop. Astr., 50, 233.

———. 1943, Pub. Obs. U. of Michigan, 8, 149.

———. 1945, Pub. A.S.P. 57, 69.

———. 1953, Ap.J., 117, 279.

———. 1960, Stellar Atmospheres, ed. J.L. Greenstein (Chicago, Ill.: U. of Chicago Press), p. 585.

———. 1963a, Sky and Telescope, 25, 206.

———. 1963b, A.J., 68, 541.

McMath, R.R. 1941, Pub. Obs. U. of Michigan, 8, 95.

McVittie, G.C. 1950, M.N., 110, 224.

———. 1951, Problems of Cosmical Aerodynamics, ed. J.M. Burgers and H.C. van de Hulst (Dayton, Ohio: Central Air Documents Office), p. 71.

Maran, S.P. 1963, Harvard Announcement Card, No. 1587.

Meinel, A.B. 1963, Ap.J., 137, 834.

Milon, D. 1963, I.A.U. Circ., No. 1825.

Mumford, G.S. 1964, Ap.J., 139, 476.

Mustel, É.R. 1964, Sov. Astronomy, 6, 772.

Newsom, G., and Chester, C. 1963, Harvard Announcement Card, No. 1595.

Oort, J.H. 1946, M.N., 106, 159.

Orlov, M.Y., and Rodriguez, M.G. 1964, Sov. Astronomy, 7, 729.

Payne-Gaposchkin, C. 1957, The Galactic Novae (New York, N.Y.: Interscience Publishers).

Payne-Gaposchkin, C., and Gaposchkin, S.I. 1942, Harvard Obs. Circ., No. 445.

Pease, F.G. 1920, Pub. A.S.P., 32, 334.

Peltier, L.C. 1963a, Harvard Announcement Card, No. 1587.

———. 1963b, ibid., No. 1588.

Pipping, G. 1963, I.A.U. Circ., No. 1824.

Popper, D.M. 1940, Ap.J., 92, 262.

Pottasch, S. 1959a, Ann. d'ap., 22, 297.

———. 1959b, ibid., 22, 310.

———. 1959c, ibid., 22, 394.

———. 1959d, ibid., 22, 412.

Schmidt, T. 1958, Zs.f. Ap., 46, 145.

Schmidt-Kaler, T. 1962, Kleine Veröff. Bamberg, No. 34.

Seaton, M.J. 1960, M.N., 120, 326.

———. 1960b, Reports on Progress in Physics, 23, 313.

Seaton, M.J., and Osterbrock, D.E. 1957, Ap.J., 125, 66.

Seitter, W.C. 1963, Veröff. Bonn, No. 67.

Sobolev, V.V. 1947, Moving Envelopes of Stars, (Leningrad,

U.S.S.R.: State U. of Leningrad).

Steinon, R.M. 1963, Harvard Announcement Card, No. 1587.

Stephenson, C.B., and Herr, R.B. 1963, Pub. A.S.P. 75, 253.

Strömgren, B. 1939, Ap.J., 89, 526.

———. 1948, ibid., 108, 242.

Tull, R.G. 1963, Thesis, U. of Michigan.

Walker, M.F. 1954, Pub. A.S.P., 66, 230.

———. 1956, Ap.J., 123, 68.

———. 1962, Konkoly Info. Bull. Variable Stars, No. 2.

Whitford, A.E. 1958, A.J., 63, 201.

Wyse, A.B. 1939, Lick Obs. Pub., 14, 93.

Zanstra, H. 1931, Dominion Astrophys. Obs. Pub., 4, 209.

———. 1955, Vistas in Astronomy, 1, 256.