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THE SPECTRA OF SUPERNOVAE

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ABSTRACT

Absolute spectral-energy distributions have been obtained for a number of supernovae of Types I and II. Included is a comprehensive set of observations, spanning 230 days of the bright Type I supernova 1972e in NGC 5253. Three general conclusions are reached: (1) Both SN I's and SN II's have a continuum which changes slowly and uniformly with time and which carries the bulk of the radiated flux. (2) There exist lines in both SN I's and SN II's which have P Cygni profiles, i.e., broad emissions flanked on their violet edges by broad absorptions. (3) Lines exist which persist through the evolution of the spectrum and which are common to SN I's and SN II's.

In SN II's, spectral lines are identified as Hα, Hβ, Hγ, H and K of Ca II, the infrared triplet at λ8600 of Ca II, the sodium D-lines, the magnesium *b*-lines at λ5180, and possibly also Fe II lines. At late stages the [O I] lines λλ6300, 6363, and a line which is tentatively identified as a blend of the [Ca II] lines λλ7291, 7323 is also observed.

In SN I's spectral lines are identified as H and K of Ca II, the infrared triplet of Ca II, the sodium D-lines, and the magnesium *b*-lines. Some two weeks after maximum there is evidence that Hα and Hγ may appear. The Hβ line is in a confused spectral region and its presence cannot be verified. The strong λ4600 feature gradually drifts with time from 4600 Å near maximum light to 4700 Å after 250 days. When it is near 4600 Å it may be a blend of Fe II lines; when it reaches 4700 Å it perhaps should be identified with the He II line at λ4686.

The two SN II's observed have expansion velocities in the outermost regions of 15,000 km s^{-1}, while that of the SN I 1972e in NGC 5253 has 20,000 km s^{-1}. In the case of SN II's, some weeks after maximum light the photospheric temperature is about 5000° K and the electron density in the "reversing layer" is approximately 10^9 electrons cm^{-3}. The dilution factor at this time is approximately 10^{-2}. The number of electrons per cm^2 in the line of sight appears to be approximately 10^{24} which suggests that electron scattering is the main source of opacity. It is suggested that the chemical abundances in SN II's may be approximately solar while hydrogen may be very deficient in SN I's.

Subject headings: abundances, stellar — line identifications — supernovae

I. INTRODUCTION

The purpose of this paper is to provide a progress report on a continuing program of investigation into the nature of the spectra of supernovae. It provides a description of these spectra that is more quantitative and covers a larger wavelength range than descriptions presently available in the literature. While we have not hesitated to draw some preliminary conclusions from an examination of this new data, we have as yet been unable to reach a very deep understanding of the phenomena involved, and almost everything remains to be done in analyzing this material. It is in the conviction that this must be the work of many people that we are making these observations available.

In the past, spectroscopic observations of supernovae have been rather haphazard. The reason for this is that supernovae occur at random and can only be discovered by time-consuming searches. Most of them are 13th mag or fainter when discovered,

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TABLE 1

Observational Data

SN	NGC	Date (Max)	M_{pg} (Max)	Type	Date (Obs)	J.D. (Obs)	Bandpasses	Remarks
1969c...	3811	Feb 69	13.7	I	11 Jul 69	2440413	80/160	Near Nucleus 9E, 6N
1969h...	4725	Jun 69	15.0	I	9 Jul 69	2440411	80/160	Near Nucleus 18E, 10N
					15 Jul 69	2440448	80/160	
1969ℓ...	1058	Dec 69	12.8	II	5 Jan 70	2440591	80/160	
					14 Jan 70	2440600	80/160	
					24 Sep 70	2440853	80/160	
					21 Feb 71	2441003	80/160	
1970g...	5457 (M101)	Jul 70	11.0	II	4 Aug 70	2440802	40/ 80	Not Photometric
					8 Sep 70	2440837	40/ 80	
					15 Apr 71	2441056	80/160	HII Subtracted
					3 Jul 71	2441135	80/160	HII Subtracted
1971i	5055	Jun 71	9.7	I	18 Jun 71	2441120	40/ 80	
					20 Jun 71	2441122	40/ 80	
					3 Jul 71	2441135	40/ 80	
					27 Jun 71	2441159	40/ 80	
					28 Jul 71	2441160	40/ 80	
1971ℓ...	6384	Jun 71		I	3 Jul 71	2441135	40/ 80	
					28 Jul 71	2441160	40/ 80	
					15 Aug 71	2441178	80/160	
1972e...	5253	May 72	8.5	I	16 May 72	2441453	20/ 40	
					17 May 72	2441454	20/ 40	
					18 May 72	2441455	20/ 40	
					21 May 72	2441458	20/ 40	
					23 May 72	2441460	40/ 80	
					24 May 72	2441461	40/ 80	
					28 May 72	2441465	--/ 80	
					1 Jun 72	2441469	20/ 40	
					4 Jun 72	2441472	40/ 80	
					7 Jun 72	2441475	20/ 40	
					16 Jun 72	2441484	40/ 80	
					25 Jun 72	2441493	40/ 80	
					6 Jul 72	2441504	20/ 40	
					9 Jul 72	2441507	20/ 40	
					10 Jul 72	2441508	20/ 40	
					31 Jul 72	2441529	20/ 40	Not Photometric
					2 Dec 72	2441653	40/ 80	Not Photometric
					2 Jan 72	2441684	40/ 80	
					7 Jan 73	2441689	160/360	

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so that while they are easy to observe at first, within a month or so observations become quite difficult. The only comprehensive investigation of the spectrum of a supernova is that by Minkowski (1939) whose long series of spectra of SN 1937c (IC 4182) still provides the observational basis for all attempts to analyze the supernova phenomenon from an empirical standpoint. Review papers on supernovae have been published by Minkowski (1964) and Zwicky (1965).

Until recently almost all spectra of supernovae have been obtained photographically. Generally these spectra cover some part of the range between 3900 and 6700 Å. The few broad and indistinct emission peaks and/or absorption troughs that are visible in these spectra present a most discouraging spectacle. Since even high-resolution spectra do not show sharp features (except occasional interstellar absorption lines) (e.g., Wallerstein *et al.* 1972), there appears to be no advantage in using high resolution; thus an instrument like the multichannel spectrometer (Oke 1969) which can provide a quantitative spectrum covering the wavelength range from 3200 to 11,000 Å with a resolution of 20–80 Å is well suited to supernova observations.

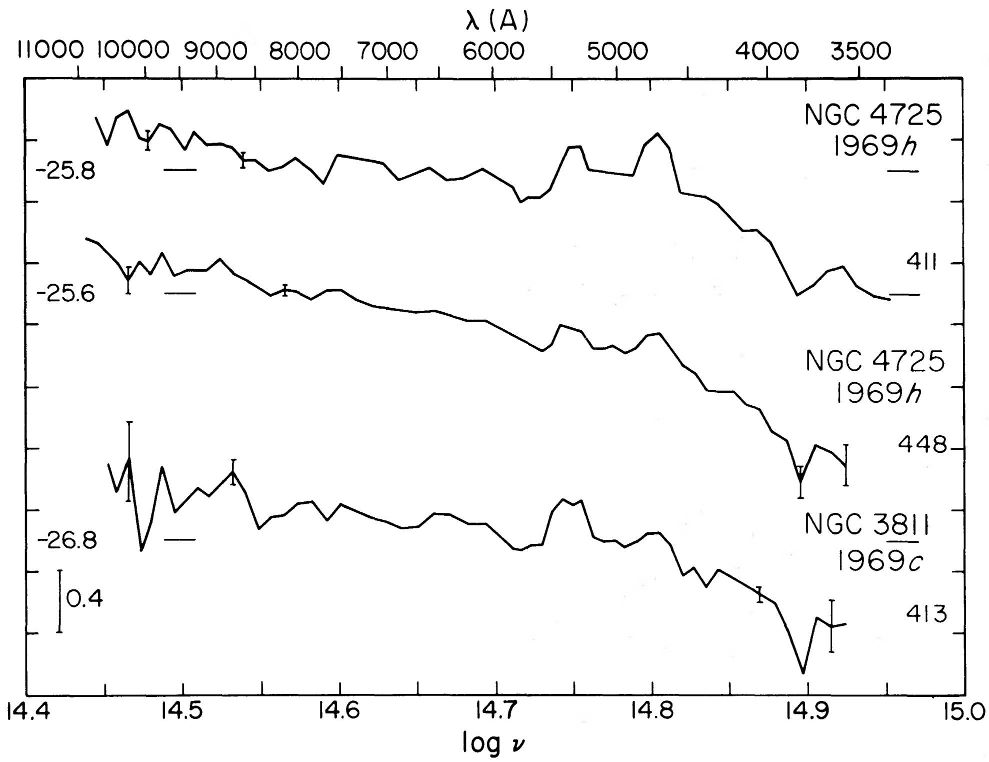

FIG. 1.—The upper two energy distributions are of SN 1969h (NGC 4725); the lowest one is SN 1969c (NGC 3811). These energy distributions are seriously contaminated by background galaxy radiation. Both are Type I supernovae.

The horizontal scale is log ν, where ν is the observed frequency in Hz. A wavelength scale is shown at the top of the figure. The vertical scale is log f_ν, where f_ν is the observed flux in ergs s^{-1} cm^{-2} Hz^{-1}. The absolute flux level is indicated at the left of each energy distribution along with a tick mark which is repeated at the right. Each energy distribution is identified by the last three digits of the Julian Day when the observation was made. Complete Julian Day, and other data are given in table 1.

Representative standard-deviation error bars are shown where they are significant towards the ends of each scan. Errors in the center part of each energy distribution (i.e., $14.55 \leq \log \nu \leq 14.85$) are normally too small to be shown.

The description above also applies to figures 2–7.

This instrument, attached to the 200-inch (508-cm) telescope, has been used since 1968 to obtain spectral energy distributions of supernovae. Since 1970 the occurrence of several relatively bright supernovae has given impetus to this work, and a fairly extensive coverage has been obtained of several supernovae of both Type I and Type II.

II. OBSERVATIONS

The supernovae for which observations have been obtained and which are discussed in this paper are listed in table 1. The table lists the supernova designation, parent galaxy, approximate date of maximum, approximate photographic magnitude at maximum, the supernova type, the dates (UT) and JD's on which spectrophotometric observations were made, and the bandpasses used. The date and the photographic magnitude are taken for the most part from Kowal and Sargent (1971).

For SN 1969c, 1969h, and 1969l all the observations were made with bandpasses of 80 Å for $\lambda < 5800$ Å and 160 Å for $\lambda > 5800$ Å. For 1970g, 1971i, and 1971l the bandpasses were generally 40 and 80 Å, with a few observations at 80 and 160 Å. The 200-inch observations of 1972e were made with bandpasses of 20 and 40 Å, while the Palomar 60-inch (152-cm) observations used a single-channel scanner and a

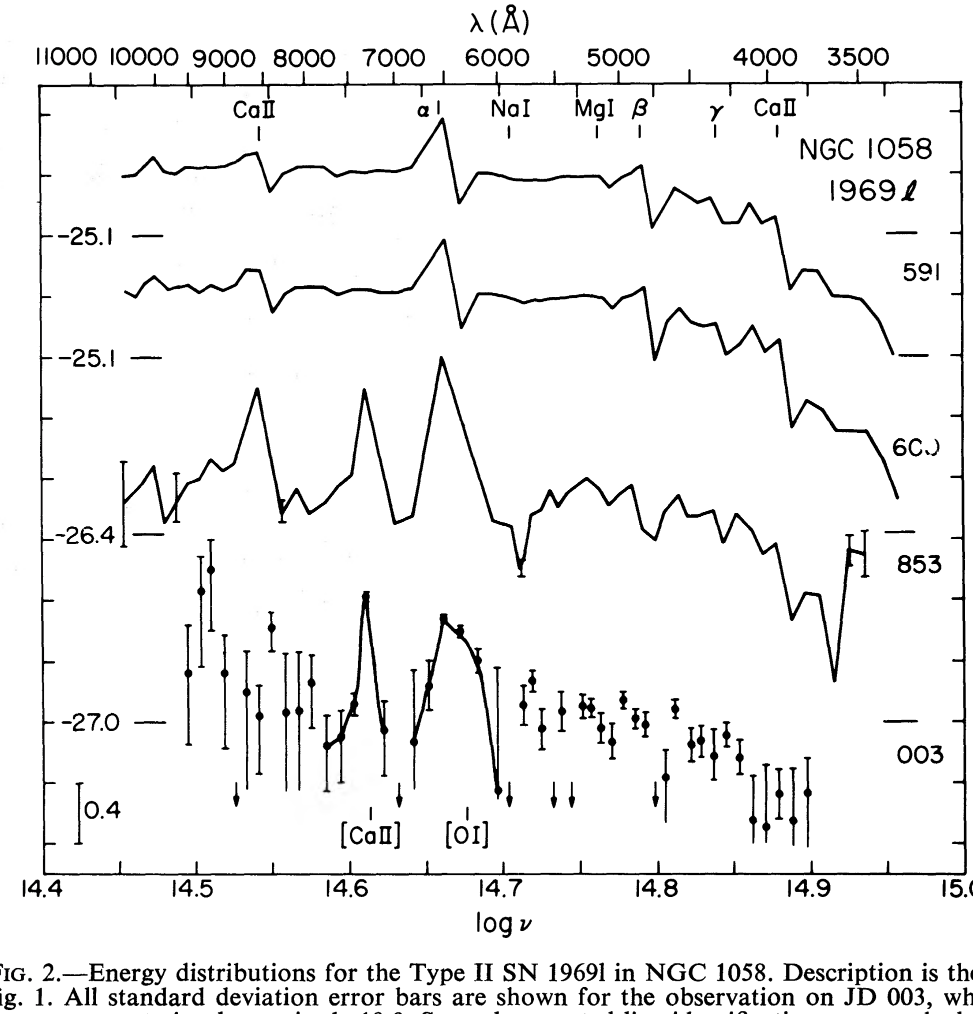

FIG. 2.—Energy distributions for the Type II SN 1969l in NGC 1058. Description is the same as fig. 1. All standard deviation error bars are shown for the observation on JD 003, when the supernova was at visual magnitude 19.0. Several suggested line identifications are marked.

resolution of 40 and 80 Å. The exceptions are multichannel observations made in 1972 December and 1973 January.

Observations were made in such a way that the entire spectrum was covered and no gaps occurred. Observations between 8900 and 9700 Å are somewhat uncertain because of the strong water-vapor absorption in the Earth's atmosphere. In particularly bad cases the observations were completely deleted over this wavelength range. This water-vapor absorption problem was particularly serious in SN 1972e which, because of its southerly declination, was always observed at large zenith distances. In some cases a nearby comparison A-type star, Boss 18446, was observed at the same time and with the same bandpasses as the supernova. It was then possible to correct accurately for the water-vapor extinction. In a few cases the extinction in the atmospheric *A*-band was not properly determined, and those observations have been deleted. The spectral energy distributions are based on the absolute calibration of α Lyrae given by Oke and Schild (1970).

Absolute spectral-energy distributions are plotted in figures 1–7 where $\log f_\nu$, the logarithm of the spectral flux density (ergs s^{-1} cm^{-2} Hz^{-1}) is plotted against $\log \nu$,

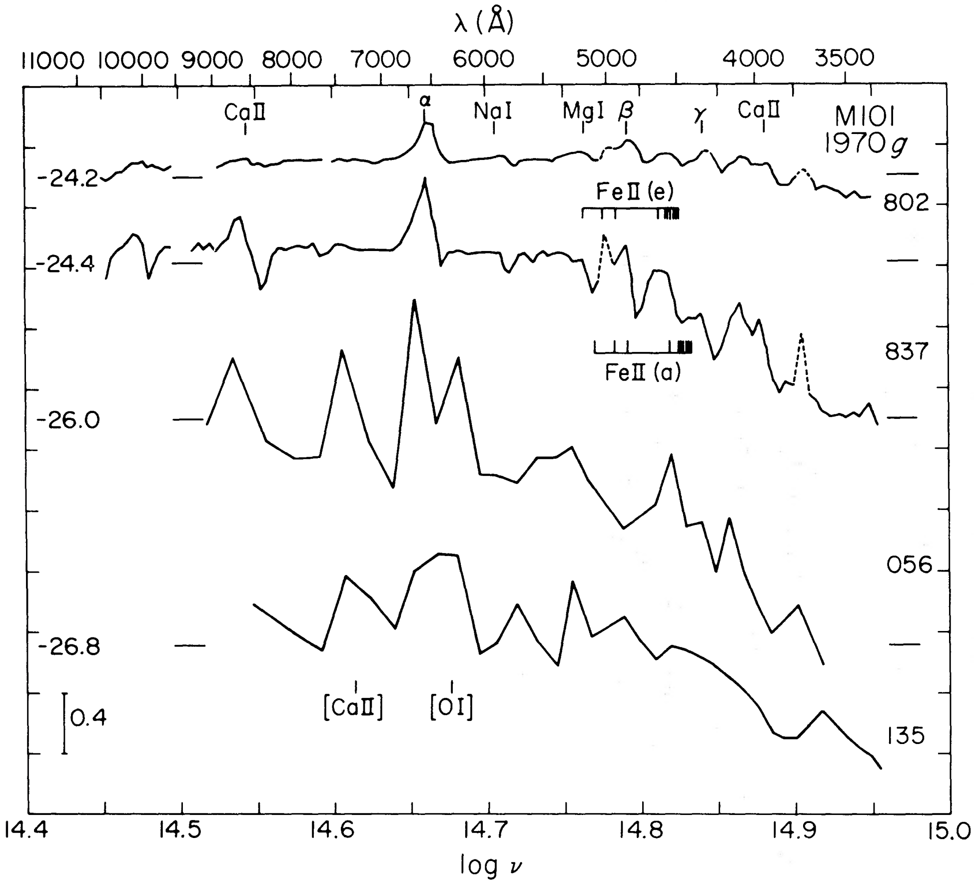

FIG. 3.—Energy distributions for the Type II SN 1970g in NGC 5457 (M101). Description is the same as fig. 1. Dotted portions of the top two energy distributions are the emission lines λ3727 of [O II] and λ5007 of [O III] which are emitted by the H II region on which the supernova is projected. For the bottom two energy distributions the background H II region (which had been previously observed [Searle 1971]) has been subtracted as well as possible. Possible line identifications of the emission peaks are marked. Positions of the strongest expected Fe II lines are shown. Emission wavelengths are plotted without velocity corrections. Absorption wavelengths are displaced by 0.008 in log ν to the violet, corresponding to the best fit of the absorption minima.

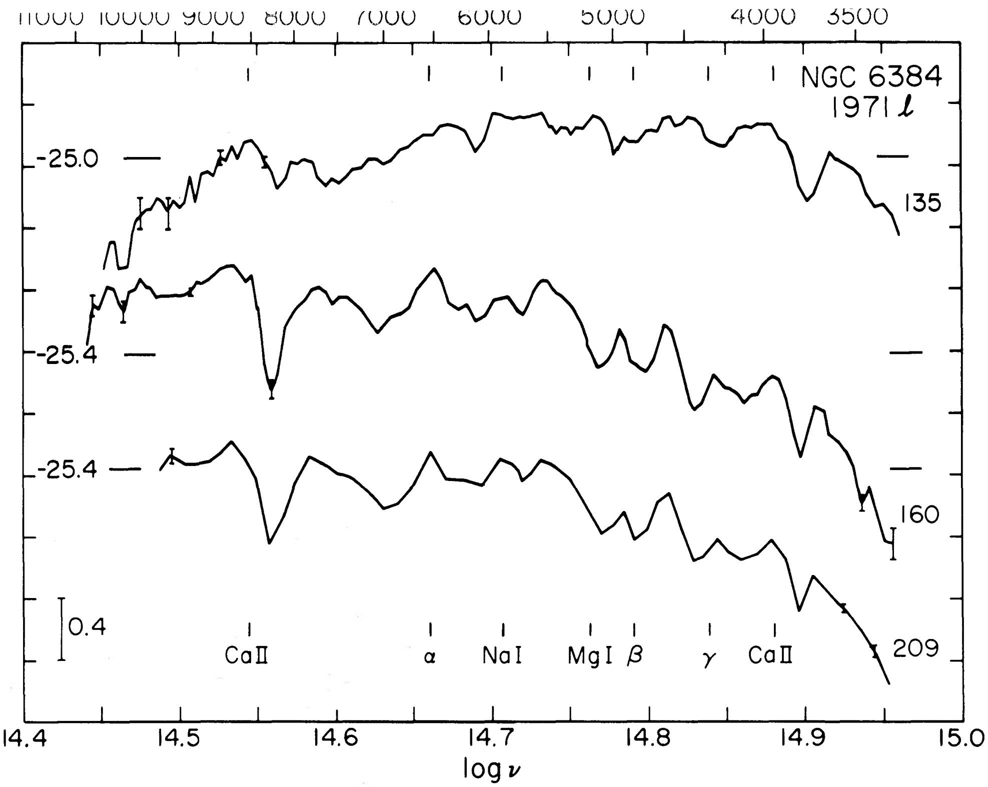

FIG. 4.—Spectral energy distributions for the Type I SN 1971l in NGC 6384. Description is the same as in fig. 1. Frequencies of Hα, Hβ, and Hγ are included for reference and do not necessarily imply that they are present in this object.

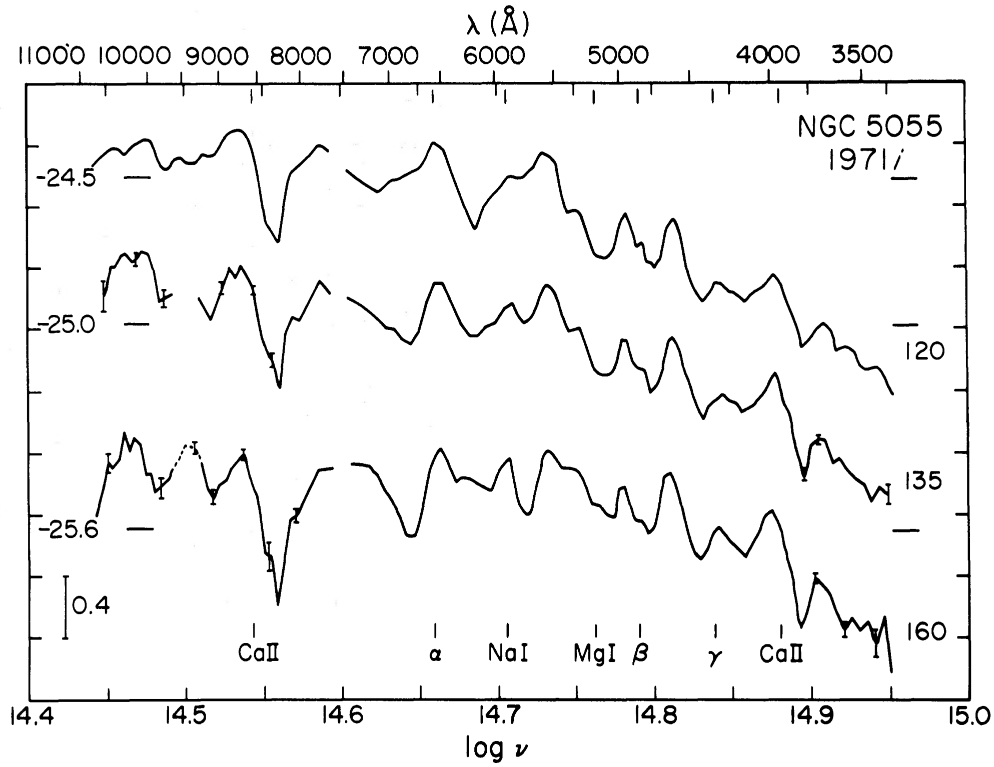

FIG. 5.—Spectral energy distributions for the Type I SN 1971i in NGC 5055. Description is the same as in fig. 1. Possible identifications of emission peaks are shown. Frequencies of Hα, Hβ, and Hγ are indicated but do not necessarily imply the existence of these lines in this object.

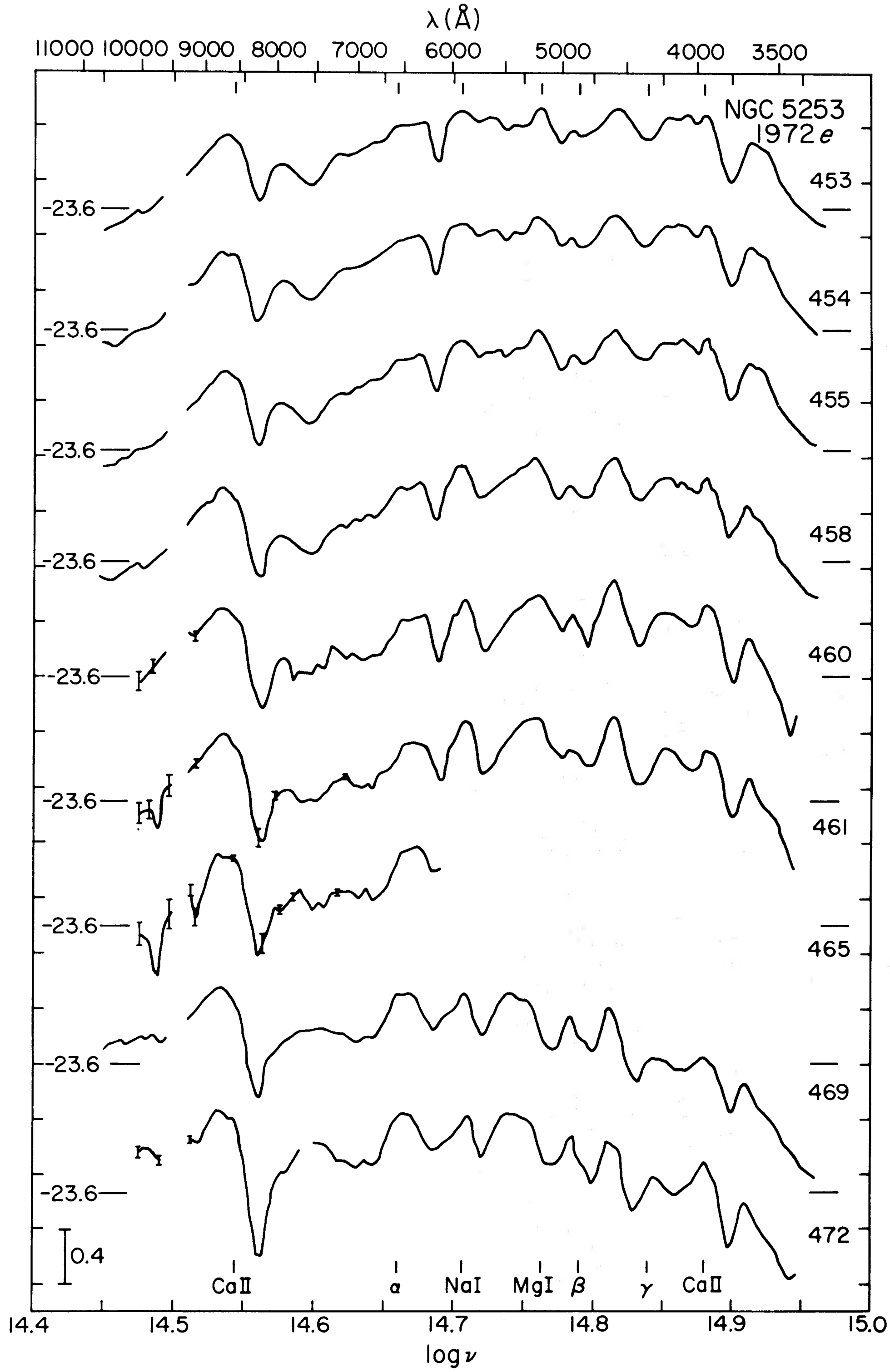

FIG. 6.—Spectral energy distributions for the Type I SN 1972e in NGC 5253. Description is the same as in fig. 1. The smoothness of the energy distributions as drawn is real since the curves go through all measured points. Possible identifications of emission peaks are shown. Frequencies of the Balmer lines Hα, Hβ, and Hγ are included but do not necessarily imply the existence of these lines.

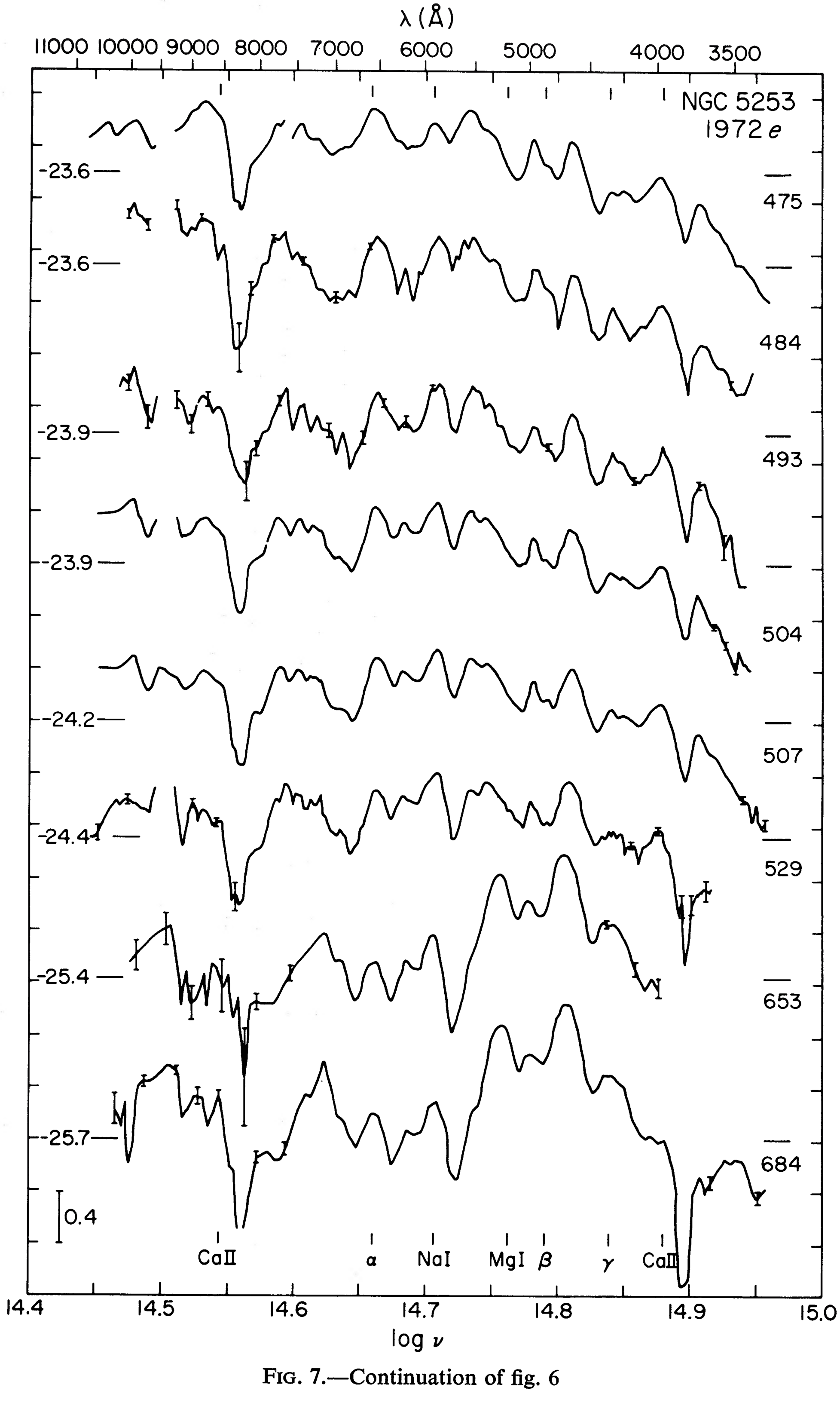

FIG. 7.—Continuation of fig. 6

where ν is the observed frequency. The only data not shown are duplicate results obtained on the same or neighboring nights which are virtually identical with those shown. All individual observed points are joined by straight lines. When observations have small errors and are closely spaced in wavelength the successive straight line segments become smooth curves. Representative standard-deviation error bars are shown where they are significant. In the central part of the spectrum from $\log \nu =$ 14.6–14.9, no error bars are shown, if they are less than ± 0.02 in $\log f_\nu$. One observation of SN 1969l (fig. 2) was obtained when it was at mag 19.0. In this case individual measured points and their standard deviations are shown.

On the left-hand side of each energy distribution is a tick and the corresponding value of $\log f_\nu$. This tick is repeated at the right. On the right hand of each energy distribution are given the last 3 digits of the Julian Day number, which is also listed in table 1. Possible line identifications are indicated in the figures along with corresponding ticks on the opposite side of the diagram. The lines Hα, Hβ, and Hγ are marked partly to provide a convenient reference. Finally, a wavelength scale is plotted along the top of each figure.

There are three qualitative facts that are immediately apparent from an examination of the observational data presented here, and each of these appears to be an important characteristic of the spectra of supernovae that has not been so clearly evident from earlier observations. These are (1) the existence of a continuum in both SN I's and SN II's which changes slowly and uniformly with time and which carries the bulk of the flux radiated by the supernova, (2) the existence of lines in both SN I's and SN II's whose shape resembles those of lines seen in spectra of P Cygni and of novae shortly after maximum light (these lines have broad emissions flanked on their violet edges by broad absorptions), and (3) the existence of lines that persist right through the evolution of the spectra and which are common to SN I's and SN II's.

III. THE SPECTRA OF SUPERNOVAE OF TYPE II

a) *The Continuum*

Our observations of Type II supernovae are shown in figures 2 and 3. These supernovae exhibit a well-defined continuum near maximum light and for at least a month following maximum. We have as yet no observations of SN II's between 35 and 250 days after maximnm. Our observations of SN II's older than 250 days show strong emission bands and some evidence that there is still a continuum.

The continuum shortly after maximum light resembles that of a blackbody at about 9500° K, but the blackbody that best fits the region between 5000 and 10,000 Å is somewhat brighter in the ultraviolet than the supernova itself. As the supernova ages the continuum becomes fainter and the temperature of the best-fitting blackbody drops rapidly to a value of about 5000° K after which it appears to remain constant (although further observations of SN II's 2 or 3 months after maximum light are needed to check this point).

We interpret these observations as indicating that the SN II has an optically thick and cooling photosphere. The fact that the photospheric temperature lies in the range 5000°–10,000° K suggests that the photosphere coincides with layers in the expanding gas mass where hydrogen is partially ionized.

As we shall discuss immediately, the line spectrum of SN II's consists of emission lines with associated violet shifted absorptions. The lines mainly redistribute in frequency the radiation from the continuum and make an insignificant contribution to the total emitted radiation. The continuum carries essentially all the energy radiated by the supernovae.

b) *Line Profiles and Expansion Velocities*

When the continuum is visible, the strongest features in the spectra of SN II's have a characteristic P Cygni shape. Typically, a broad emission band is flanked on the short-wavelength side by a broad absorption trough. Profiles of the lines at 8600, 6500, 4800, and 3900 Å can all be characterized in this way, although their profiles are not identical.

The shape of the 8600 Å line is well defined, because of the smooth continuum, and is shown in figure 8 for SN 1970g in M101 on JD 837. (Here and hereafter we shall give only the last three digits of the Julian Date for brevity.) The zero net equivalent width for the emission and absorption pair suggests that this line and those like it are formed by scattering in a differentially expanding reversing layer. If so, the maximum expansion velocity will exceed the apparent approach velocity of the absorption trough and the apparent recession velocity of the emission peak. Estimates of the expansion velocity obtained from the extreme violet edge of the absorption V_v, or from the red edge of the emission, V_r, for this supernova give $|V_v| = |V_r| = 15{,}000$ km s^{-1}. For SN 1969l in NGC 1058, the corresponding values are also about 15,000 km s^{-1}.

The expansion velocity of the bulk of the material forming the reversing layer will

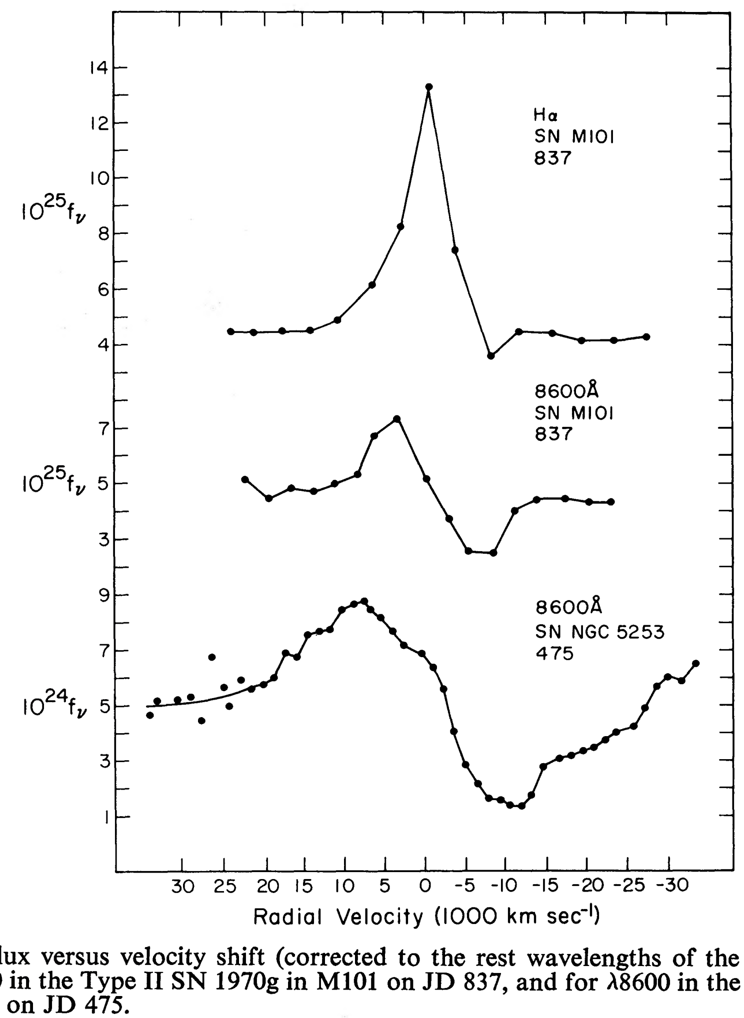

FIG. 8.—Flux versus velocity shift (corrected to the rest wavelengths of the galaxy itself) for Hα and λ8600 in the Type II SN 1970g in M101 on JD 837, and for λ8600 in the Type I SN 1972e in NGC 5253 on JD 475.

be smaller than the maximum velocity, and the expansion velocity at the photosphere will be smaller still (though the photosphere is not a material layer). Since $|V_v| = |V_r|$, the photosphere occults only a small fraction of the receding hemisphere of the reversing layer. If $|V_r| = (1 - \epsilon)|V_v|$, then the ratio of the photospheric radius r, to the maximum radius, R, is $r/R = (2\epsilon)^{1/2}$. For $\epsilon < 0.1$, $r/R < 0.5$. From the absence of occultation effects we conclude that the material forming the reversing layer is bathed in a radiation field which is appreciably diluted. We see that the dilution factor $W \simeq \frac{1}{4}(r/R)^2 < 0.06$.

The Hα profile, shown in figure 8 for the same supernova, shows net emission, with the emission peak centered near the rest wavelength, in the rest frame of M101. The width of the line, from the red edge of the emission to the blue edge of the absorption, is about the same as for the 8600 Å line. This suggests that the two lines are formed within the same volume, so that conditions inferred from the Hα line apply to the whole reversing layer.

c) *Some Tentative Line Identifications*

i) *Balmer Lines*

The Balmer series is certainly present in the spectra of SN II's. We interpret the net emission in Hα as resulting from hydrogen recombination in the reversing layer. In particular consider the observations of SN II 1970g in M101 obtained on JD 837. The net observed flux in the Hα line is 1.0×10^{-11} ergs cm^{-2} s^{-1}. Adopting 6500 kpc as the distance of M101 this corresponds to 9×10^{40} ergs s^{-1} emitted at the source or 3×10^{52} Hα photons s^{-1}.

The expansion velocity of the outermost edge of the emitting volume has already been estimated to be 15,000 km s^{-1}, so that at this epoch, some 40 days after the expansion began, the emitting volume will be $\lesssim 6 \times 10^{47}$ cm^3. These estimates require an electron density $n(e) \gtrsim 7 \times 10^8$ cm^{-3} in the reversing layer to produce the observed Hα line. Since, under these conditions the recombination time is only a few hours, a mechanism must be found to keep the hydrogen ionized. The observed flux on JD 837, with an approximate photospheric temperature of 5000° K, requires a photosphere of dimension $r = 1.8 \times 10^{15}$ cm. Then $W \simeq 0.04$ for the outermost layers. Sufficient ionizing radiation from this photosphere (if it is a blackbody) can only be obtained if ionization occurs from the $n = 2$ level of hydrogen. The population required in this level is 10 cm^{-3} and this can be maintained if Lα is trapped in the reversing layer. The observations show that there is a Balmer jump and, under conditions stated above, the optical depth from the reversing layer beyond the Balmer limit is approximately unity as required. The above picture also indicates that there are 2×10^{24} electrons cm^{-2} in a column through the reversing layer. It is significant that this just suffices to make the reversing layer optically thick from electron scattering. If the material in the reversing layer is mostly ionized hydrogen, we estimate from the above figures that the mass of gas in the reversing layer is about 0.3 $\mathfrak{M}_\odot$.

ii) *Lines of* Ca II, Na I, *and* Mg I

Apart from the Balmer lines, the strongest features in the spectra of SN II's are those at λλ3950 and 8600. An analysis of the facts concerning the continuous spectrum and Balmer line profiles leads us to the view that the reversing layer consists of a differentially expanding tenuous mass of gas with $n(e) \simeq 10^9$ which is irradiated by a dilute photospheric radiation with $W \simeq 10^{-2}$ and $T_c \simeq$ 5000°–10,000° K. The lines to be anticipated are those arising from the ground state or metastable states of ions that will be abundant in such an environment. In general, lines that are present in A- and F-type supergiants and in shells surrounding A and F stars might provide suitable search lists.

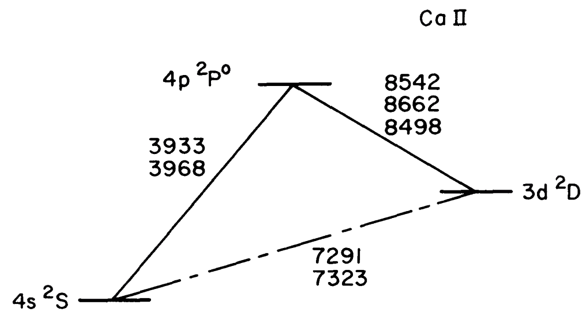

FIG. 9.—Energy level diagram for Ca II showing the relationship among the H- and K-lines, the infrared triplet, and the forbidden lines.

This point of view leads us to suggest that the line λ3950 is to be identified with the H and K lines of Ca II and that the λ8600 feature is to be identified with the Ca II infrared triplet λλ8498, 8542, 8662 which arises from the strongly metastable $3d\,^2D$ level and whose upper level is also the upper level of the H and K resonance transitions (see fig. 9).

We now consider the ionization states of calcium and sodium. The equation for the ionization equilibrium $X^+ + h\nu \leftrightarrows X^{++} + e$ in a dilute radiation field is

$$\frac{n(X^{++})}{n(X^+)} = \frac{W(W+Q)}{(1+Q)}\left(\frac{T_e}{T_c}\right)^{1/2}\frac{n^*(X^{++})}{n^*(X^+)}, \quad (1)$$

where the starred values refer to the equivalent thermodynamic system, W is the geometrical dilution factor of the radiation whose color temperature is T_c, and T_e is the electron temperature (and *the* temperature of the equivalent thermodynamic system). The quantity Q is the ratio, in thermodynamic equilibrium, of photoionizations from the ground state to photoionizations from excited states. Adopting $T_e \simeq T_c \simeq 5000°$ K, the values of Q are 2×10^{-1}, and 3×10^{-4} for the Ca^0 and Ca^+ photoionizations, respectively (using the cross-sections of Seaton 1951), and we find that with $W = 10^{-2}$ essentially all Ca will be Ca^+ if $10^6 < n(e) < 10^{12}$. As we have seen, the Balmer emission implies that $n(e) \simeq 10^9$ and under these circumstances, since there are 10^{24} electrons cm^{-2} in a column through the reversing layer, it is hardly surprising that the Ca II lines are prominent features in SN II spectra.

After the Balmer series and the Ca II lines, the strongest unblended features in the spectra of SN II's are λλ5890 and 5180. The first of these could either be λ5876 of He I or λ5890 of Na I (the D-lines). We prefer the latter attribution because none of the other strong triplet lines of He I occurs in the spectra of SN II's. With the conditions that we have estimated, most sodium atoms will be once ionized, but from equation (1), with the appropriate value of Q (which is 3×10^{-4}), we find that about one sodium atom in a thousand will be neutral. Sodium and calcium are about equally abundant in solar material and while we cannot know whether this is also true in supernovae shells, it is reasonable to expect that weak lines of Na I should coexist with strong lines of Ca II.

An analysis of the other lines from cosmically abundant species which might be expected to occur under the conditions that we have inferred to exist in SN II envelopes, shows that the resonance lines of Ca I and lines arising from metastable states of Mg I and Fe II are the most promising candidates. The line λ4226 of Ca I is not clearly present in our scans of SN II's. However, it falls in a blended region of the spectrum, and it could be as strong as the D-lines and yet remain undetected. From equation (1) we find that the ratio Ca^0/Na^0 is roughly proportional to the dilution factor in the regime of interest and has a value near unity for equal abundances under our nominal conditions. It appears that the presence or absence of λ4226 in the spectra of SN II's will depend rather critically on the precise physical conditions that obtain. It is of some interest that this line is weak or absent in the spectra of shell stars where the D-lines are strong.

On the other hand, in shell stars with strong D-lines the lines of Mg I that arise from metastable levels are usually also strong. It seems to be a fairly safe inference that the feature at λ5180 in the spectra of SN II's is to be attributed to the Mg I *b*-lines.

iii) *The Feature at λ4600*

The identifications so far proposed account for nearly all the features that are present in the scans of SN II's in the month following maximum light. The exception is the feature, prominent in the spectrum of SN 1970g in M101 obtained in 1970 September, which is blended with Hγ, but whose emission peak and absorption trough give a wavelength of λ4600. The only resonance line in the vicinity is λ4607 of Sr I, but since under the conditions we have inferred nearly all strontium will be once ionized, and since λ4077 and λ4215 (the resonance lines of Sr II) do not occur in the spectrum this possibility must be rejected.

The continuous and line spectra of SN II's most closely resemble the spectra of A supergiants, of shells around late B stars and of novae under maximum light. The spectrum of Nova Herculis 1934 obtained on the evening of December 13 is illustrated in Stratton's monograph (1936). The line features are much weaker relative to the continuum and are much narrower than in SN II's but the general character of the spectrum is quite similar to that of SN II 1970g in M101 for JD 837. In this spectrum of Nova Herculis, apart from the Balmer lines and the H- and K-lines, the strongest feature is a complex emission band, with an intensity comparable to Hβ, in the region between λλ4500 and 4600 and which is produced by transitions in multiplets 37 and 38 of Fe II. This band is flanked by a strong absorption, comparable to that of Hδ, caused by Mg II λ4481 absorption. In shell star spectra the lines of multiplets 37 and 38 of Fe II which arise from metastable levels are among the strongest features. Three other very strong Fe II lines are λλ4923, 5018, and 5169 of multiplet 42. If our general picture of the physical structure in SN II's has any validity, it is hard to escape the conclusion that these lines will produce strong spectral features in supernovae too. Both the emission and absorption positions of these lines are plotted in figure 3. While the fits are not perfect, we suggest that they do contribute to both the emission and absorption spectra of SN II's. A similar conclusion based on the absorption features has already been reached by Patchett and Branch (1972).

iv) *Lines of* [O I]

In figures 2 and 3 those observations of SN 1969l in NGC 1058 and SN 1970g in M101 obtained 8 months or more after maximum light show two conspicuous differences from those obtained in the month following maximum. These are the appearance in the late phases of two strong emission features that do not occur at all in the early phases. These emissions, which rival Hα itself in intensity are located at λλ6300 and 7300. Only in the spectrum of SN 1970g on JD 056 is the λ6300 line clearly separated from Hα. In the remaining scans, the line is blended with the Hα, but apparently present. This is verified by slit spectra taken at comparable times by Gunn and which are illustrated by Kirshner (1973).

It seems fairly likely that the feature at λ6300 is the [O I] doublet at λλ6300 and 6363. These lines, which occur in the spectra of novae and in some shell stars, are prominent in the spectra of shock excited gases of some supernova remnants. Minkowski (1939) reported their appearance in the spectrum of the Type I supernova 1937c in IC 4182, about 180 days following maximum light and on subsequent dates. They have not previously been reported in SN II spectra.

A hot neutral gas is required to produce these lines in strength. In addition the electron density must be less than $\sim 10^5$ cm^{-3} for radiative de-excitation of the upper level of this transition to predominate over collisional de-excitations. We suggest that the reversing layer, which in the month following maximum light consists of ionized gas with $n(e) \sim 10^9$ cm^{-3}, contains, 8 months after maximum light, substantial volumes of neutral gas with $n(e) \leq 10^5$ cm^{-3}. The reduction in density by a factor of 10^4 does not seem implausible in view of the fact that the emitting volume has increased by a factor of 10^3 in this interval of time due to the expansion of the supernova.

v) *The Line at λ7300*

Two possible identifications suggest themselves for the strong emission line at λ7300 which appears in the later spectra of SN II's. It could be λ7320 + λ7330 of [O II] or it could be λ7291 + λ7323 of [Ca II]. The excitation potential of the upper level of the λ7320 transition in [O II] is 4 eV, and it is unclear how this could be excited collisionally without producing, at the same time, other permitted and forbidden lines of the abundant once-ionized metals with comparable intensities as happens, for example, in the spectra of novae. The great strength of this line at λ7300 in the later phases of SN II's and the fact that, in the case of SN II 1969l in NGC 1058, it is not accompanied by any other emissions that can be identified with other well-known forbidden lines leads us to doubt the identification with [O II].

The [Ca II] lines at λλ7291 and 7323 form a transition that connects the metastable lower level of the λ8600 transition with the ground state of the ion. In the first month after maximum light, the λ8600 line in SN II's shows a P Cygni profile with a zero net equivalent width. This implies that the depopulation of the $3d\,^2D$ level is almost exclusively by radiative reabsorptions in the λ8600 line rather than by alternative processes, the most important of which are expected to be collisional and radiative transitions to the ground state and photoionizations resulting from absorption of Lα photons.

At some time between 1 and 8 months after maximum light the character of the line profile of the feature at λ8600 appears to change and the line develops a strong net emission. Evidently the $3d\,^2D$ level must, at these late phases, be depopulated by some mechanism other than radiative absorptions in λ8600. It is tempting to suppose that, at these late phases, both the energy density in the radiation field and the electron density are sufficiently low that radiative downward transitions in the λλ7291, 7323 lines become the preferred route for depopulating the $3d\,^2D$ level. In these circumstances the lines at λλ8600 and 7300 must clearly have very nearly the same intensity, as indeed they are observed to have. However, the number of photons observed in these emission transitions is larger than the number absorbed at the H- and K-lines. As pointed out to us by Mr. J. Kwan, this can probably be explained if there is a high degree of trapping of H and K photons in the expanding envelope. Detailed studies of this are under way.

In deciding which identification is correct for the line at λ7300 it will clearly be of the greatest importance to follow in detail (and with rather higher spectral resolution than we have in fact used so far), the development of the λ7300 line in SN II's between 1 and 8 months after maximum light.

IV. THE SPECTRA OF SUPERNOVAE OF TYPE I

a) *The Continuum*

Inspection of the scans of SN I's illustrated in figures 4, 5, 6, and 7 shows that as in the case of SN II's, there is a continuum which cools as the supernova ages.

As shown in Kirshner *et al.* (1973), the best-fitting blackbody temperature of this continuum near maximum light is about 10,000° K and this falls to ~7000° K some 2–3 weeks after maximum and thereafter remains constant. The smooth and gradual change with time of the overall shape of the spectrum is a very striking phenomenon and clearly shows that the SN I spectrum is not a superposition of emission bands but that, just as in SN II's the bulk of the energy radiated by the supernova is contained in a continuum; the net flux in line radiation is relatively insignificant.

b) Line Profiles and Expansion Velocities

The line spectra of SN I's are clearly much more complicated than those of SN II's. This is emphasized in figure 10 where spectra of the two types are shown at what we judge to be comparable phases. It is also clear that the strongest features of SN II's appear also among the strongest and most persistent features in SN I's. In particular, the features near λλ3900 and 8600 which we identified in SN II's with transitions in Ca II are prominent in Type I spectra during the first two months following maximum light. The lines in SN I's have a characteristic P Cygni profile, as shown in figure 8. Here the 8600 Å line shape is somewhat irregular, and no doubt blended, but the essential feature, a symmetrical emission and absorption centered near the rest wavelength, is present in this SN I just as in SN II's. The red edge of the emission peak indicates a recession velocity of about 20,000 km s^{-1}, while the blue edge of the absorption, though less well-defined, shows a shift that is at least as large. Due to uncertainties in the continuum, no clear inference can be drawn about the geometry of the photosphere and reversing layer.

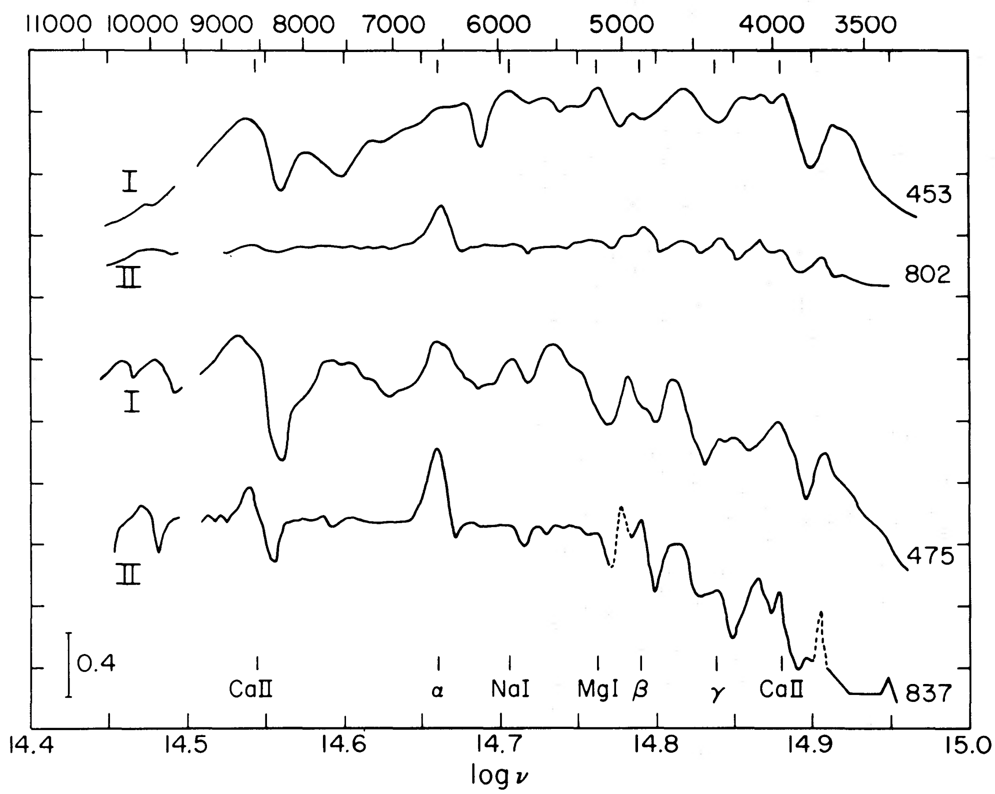

FIG. 10.—Comparison of spectral energy distributions of Type I and Type II supernovae at two selected phases. The Type I curves are from SN 1972e while those for Type II are from SN 1970g.

c) *The Problem of Line Identifications in Type I Supernovae*

In figure 11 we have attempted to summarize the evolution of the spectrum of the Type I supernova 1972e in a fashion analogous to that used by Minkowski (Zwicky 1965). The horizontal scale is the same as in previous figures. The vertical scale is the time, in Julian Days, plotted on a logarithmic scale with zero arbitrarily chosen as JD 450. The solid lines with arrows pointing upwards mark frequencies of the emission peaks. The remaining lines correspond to the observed minima in the energy distributions. Only the most obvious features are shown. The diagram represents what we believe to be a typical spectral evolution for Type I supernovae, but it should in no way be taken as a substitute for the primary data of figures 4, 5, 6, and 7.

This plot shows, as do figures 7 and 8, that there are four strong features in the spectrum that persist throughout the supernova's evolution. These features each consist of an emission peak and an associated blue-shifted absorption. The emission peak wavelengths of these features are at λλ8700, 5890, 4600, and 3970. The peak at λ8700 is not well defined in wavelength and appears to be a blend of two emission peaks, one of which is near λ8600.

It is striking that these four emission peaks coincide very closely with the strongest features (other than the Balmer lines) in the spectra of Type II's. We suggest that they are, in fact, the *same* features and that there is a basic similarity between the spectra of the two types of supernovae.

The differences, of course, remain real enough! Beside the four stable features in the spectra of SN I's there are many other features, of which the stronger ones are

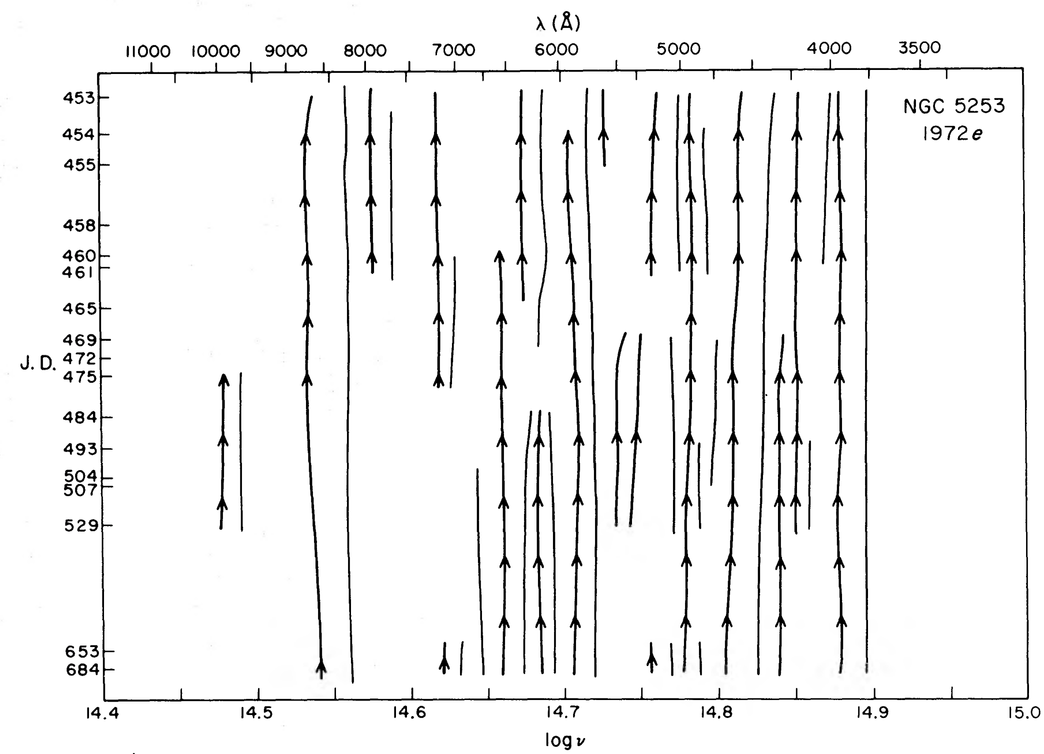

FIG. 11.—Development with time of the spectrum of 1972e in NGC 5253. Vertical scale is the JD, plotted logarithmically, arbitrarily assuming the zero to be at 450 days. Lines with arrows pointing up are emission peaks, other lines are absorption troughs. Only the most prominent features are shown. Only one feature, that at 4600 Å and the corresponding absorption near 4400 Å, appears to drift significantly in wavelength with time.

shown in figure 11. From an empirical point of view they are described well enough by figures 4, 5, 6, and 7, but they are very difficult to analyze. Inspection of figure 11 shows that there is only one emission-absorption feature, that at 4600 Å, which drifts appreciably in wavelength with time. All other features seem to be fixed in wavelength, particularly when allowance is made for the fact that many features are blends in which one component may drop out and another one strengthen during the time development. It is often difficult to determine how many lines are in a blend let alone to specify the wavelengths. The identification problem in the spectra of Type I supernovae remains one of great difficulty.

Of particular interest is the question of whether Balmer lines exist in Type I supernovae spectra. During the first two weeks of its evolution, there are no signs of Balmer lines except perhaps Hα. However, beginning on JD 460 in SN 1972e a strong emission line does appear in the expected position of Hα and it persists at least until JD 684. At about the same time a feature also appears in the position of Hγ. Near Hβ, the spectra are complex and seriously blended and it is not possible to determine whether Hβ is present or not. Figure 10, which compares Type I's and Type II's, illustrates the case for and against Balmer lines in Type I's. The evidence in favor is, in our opinion, good, but in a highly blended spectrum doubts must remain.

We think that the conclusion is inescapable that the main features which contribute to the spectra of SN II's are also prominent contributors to the spectra of SN I's. The differences between the two types is in the relative strength of these features and, particularly, in the fact that spectral features are generally much stronger and much more numerous in Type I's. It is interesting to speculate on why this might be if, as all the evidence indicates, the basic physical situation is rather similar in Type I's and in Type II's. It appears probable that there are more ions of the common metals per free electron in the material of the envelopes of Type I's than Type II's. Since there are no convincing coincidences in the spectra of supernovae of either type with lines of He I or He II during the early phases, it appears that helium must be neutral in these envelopes while hydrogen appears to be mostly ionized. We tentatively suggest that the material in the envelopes of SN II's may be of roughly solar composition while that of SN I's may be hydrogen poor and helium rich. It is quite possible, of course, that even more far-reaching composition differences may be involved. The essential hypothesis that we suggest is that one basic difference between Type I and Type II supernovae is in the chemical composition of their envelopes.

d) *Similarities in the Spectra of Type I Supernovae*

It has often been suggested that spectra of Type I supernovae show remarkable similarities. We have available excellent data to investigate this question. With reference to SN 1972e in NGC 5253, it can be seen from figures 6 and 7 that the spectrum changes day by day from JD 453 to about 465. Between JD 460 and 469 several features disappear while a number of new ones become visible. From JD 469 until 507 the spectrum remains remarkably constant. Between JD 507 and 529 the feature at λ5550 begins to fade and has almost disappeared by JD's 653 and 684.

Now compare the scans of SN 1971i in NGC 5055 (fig. 5) with those of SN 1972e. As can be seen, the energy distribution for JD's 120 and 135 are almost identical and match very accurately 1972e between JD's 469 and 507. Also the spectrum of 1971i on JD 160 fits that of 1972e on JD 507. Thus the time development of the spectrum of 1971i is completely compatible with that of 1972e. Maximum light probably occurred in late 1971 May.

Next we compare SN 1971l (fig. 4) and SN 1972e. The spectrum for JD 135 fits that of SN 1972e on JD 453. The spectra on JD 160 and 209 are almost identical and fit SN 1972e between JD's 469 and 507. Again, the rate of time development of the two supernovae is comparable.

The two other Type I supernovae which we have observed are 1969h in NGC 4725 and 1969c in NGC 3811. Energy distributions are shown in figure 1. A comparison of these spectra with those of 1972e show that they are very different in that their features are much weaker than in SN 1972e. However, each supernova lay very close to the nucleus of the parent galaxy (the distances are given in table 1), and it is almost certain that the energy distributions are strongly contaminated by the light from the galaxy itself. In fact, adding the energy distribution of a normal galaxy (Oke and Schild 1970) to those of SN 1972e at suitable phases, reproduces the observed energy distributions very well. The strong features in the energy distributions of SN 1969h on JD's 411 and 448 match those of 1972e on JD's 653 or 684 quite well. Maximum light probably occurred in 1968 December or 1969 January rather than 1969 June as given in table 1 and as listed by Kowal and Sargent (1971).

In the case of SN 1969c in NGC 3811, the observed energy distribution suggests a match with 1972e on JD 653 or 684. This would put maximum light for this supernova in 1968 December or 1969 January instead of 1969 February as listed in table 1.

A very detailed comparison can be made between SN 1937c in IC 4182 and SN 1972e by comparing the spectra published by Minkowski (1939) with our data in figures 6 and 7. Because of the different nature of the observations, only detailed spectral features can be compared rather than overall energy distributions. Of particular value for the comparison are the rectifications of the SN 1937c spectra as given by Greenstein and Minkowski (1973) in their figures 2 and 3. Over the common spectral range, it appears that the spectra of the two supernovae are apparently almost identical when compared at the appropriate phases. Furthermore, the rates of development of the spectra with time are the same, as far as can be determined, up to at least 225 days after maximum. The comparison of spectra over the first three weeks indicates that SN 1972e on JD 453 corresponded to SN 1937c 8 days after its maximum as determined by Minkowski (1939).

V. COMMENTS ON EARLIER WORK

The early view of the nature of the spectra of supernovae (Minkowski 1939, 1941), which has been widely accepted until quite recently was that they consist of emission bands of highly excited and ionized gases. In the case of SN II's these were thought to be emission lines of permitted transitions in H, He, C, N, and O by analogy with those seen in the "diffuse" and "Orion" phases of novae. These lines in Type II's were thought to be superposed upon a continuum and often to be flanked by P Cygni-like absorptions. In the case of Type I's the emission band were thought to be overlapping and the contributing lines could not be identified. In supernovae of this type it was thought that no continuum was visible. Attempts to relate views like these to the observations (e.g., Whipple and Payne-Gaposchkin 1941; Gordon 1972) have not met with much success, and the new data presented in this paper show quite clearly that supernova spectra are of an essentially different character.

A good deal of earlier work has led to views similar to our own regarding the character of the spectra of SN II's. Arp (1961) concluded from *U*, *B*, *V* photometry of SN II 1959d in NGC 7331 that the main part of the light consisted of continuum radiation from a cooling, expanding, photosphere which resembled the atmospheres of A and F supergiants. Branch and Greenstein (1971) analyzed the spectrum of an atypical SN II 1961v in NGC 1058 (a Type V in Zwicky's 1965 terminology). They showed its close resemblance to the "principal" spectrum of novae. Recently Patchett and Branch (1972) have found that many of the absorption features in SN II's can be identified as blueshifted absorption lines of hydrogen and Fe II. The work reported here confirms and extends these results emphasizing in addition the essential role played by resonance scattering and showing that the main features in the spectrum arise from transitions in H I, Ca II, Na I, and Mg I, with Fe II playing a relatively minor role.

With regard to the spectra of Type I supernovae, much recent work has been based on the hypothesis that the spectrum consists of blended absorption lines cutting into a continuum. Pioneered by McLaughlin (1963), this viewpoint was developed by Pskovskii (1968) and Mustel (1971*a*, *b*, 1972) and most recently by Branch and Patchett (1973). There is general agreement among recent authors that absorptions due to Na I, Si II, and especially Fe II are important contributors to the spectra of SN I's. Our own conclusions are in partial accord with this point of view. However, we suggest that in Type I's as in Type II's, resonance scattering plays an essential role and that the basic character of the spectrum is a superposition of P Cygni profiles upon a continuum. The hypothesis of blended absorption lines without associated emission lines cannot account for the fact that minima in the spectra of SN I's are so frequently displaced from their neighboring redward maxima *by the same velocity shift*. This fact and the direct comparison shown in figure 10 between the spectra of Type I and Type II supernovae show rather clearly that the basic character of the spectrum is the same in supernovae of both types. Not only are the line profiles qualitatively similar in the two types but so are the continua. It is sometimes supposed that SN I's are very deficient in ultraviolet radiation near maximum light compared to SN II's. However, our observations show that the observed continua are very similar, and undergo similar evolution with time.

An interesting and original view of the nature of the light emitted by a supernova outburst has been put forward by Morrison and Sartori (1969). In their picture, the observed light comes from gas surrounding the exploding star, which has been excited by ultraviolet radiation from it. Although their suggestion has been subject to criticism on theoretical grounds, it did account for the observed light curve in the visible, identify the principal lines as He II, and account for some of the redward drift in emission peak wavelengths.

When compared with this new data, the principal shortcoming is its failure to account for the strong observed continuum. In their picture the continuum, formed by two-photon decay of metastable He II, has only about 8 percent of the strength of the lines; in contrast we find that the bulk of the energy is carried by the continuum. Furthermore, only one feature, that at 4600 Å, appears to drift in wavelength with time, while their picture requires all the lines to drift together. Because of the severe blending of lines it is not possible to rule out the presence of He II lines in SN 1972e. One can even make a case for the presence of several weak He II lines at the very early phases, but between JD 475 and 529 the evidence for He II is very weak. It should also be noted that by JD 684, the 4600 Å feature has drifted to 4700 Å and coincides approximately with the expected position of λ4686 of He II. But at this phase the only Pickering series lines which may be present are those which coincide with Balmer lines. If He II lines actually do exist in SN I's, they do not carry an appreciable fraction of the flux at any phase we have observed.

The observation of Type II energy distributions indicates that the bolometric luminosity decreases with time. This seems to contradict the pulsar-powered model of supernovae sketched by Ostriker and Gunn (1971), in which the power delivered to the supernova envelope remains roughly constant.

Several features of our Type II observations correspond reasonably well to the models of Grassberg, Imshennik, and Nadyozhin (1971). In particular, we note that the photospheric diameters, expansion rates, and temperatures correspond to their shocked red giants. The observation that the temperature initially decreases, and then is roughly constant near 5000° K, agrees with their "cooling-wave" phenomenon in which the boundary of the photosphere is determined by electron opacity. Inside the photosphere, hydrogen is ionized, and the opacity is high; outside, hydrogen is neutral and the opacity low. The boundary, which is the photosphere, is also the boundary of ionization, and is, therefore, maintained at a constant temperature of about 5000° K.

VI. REMARKS

The observations presented in this paper indicate that a great deal can be learned from relatively low resolution spectra or spectrophotometric measurements of supernovae. If our picture concerning resonance scattering is correct, then even broad band photoelectric measurements are very worth while since they can be used to estimate temperatures. Much more work needs to be done at the very early phases of the outburst when the temperatures may be very high. Also observations at very late phases, particularly in the red, are very desirable to look for lines such as λλ7291, 7323 of [Ca II] and λλ6300, 6363 of [O I].

With accurate expansion velocities and temperatures, particularly in the early phases of the outburst, it should become possible, with better knowledge of the various physical processes occurring, to determine absolute luminosities of supernovae independent of any other distance criterion. This clearly is of great potential importance in establishing the cosmological distance scale.

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