OBSERVATIONAL DATA ON NOVAE AND SUPERNOVAE

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Abstract. The first half of the paper contains a discussion of the chemical composition of the envelopes of supernovae for the period close to light maximum. The principal conclusions are: The abundance of hydrogen in the envelopes of type I supernovae is low, much lower than that of nitrogen; the abundance of oxygen and carbon is also noticeably lower than that of nitrogen; it seems that there is plenty of helium and metals in these envelopes. The information for type II supernovae is more limited. But it is quite certain that the abundance of hydrogen in the envelopes of these stars is much higher than in the envelopes of type I supernovae.

In the second half of the paper the problem of supernova remnants is discussed, the circumstellar shells around supernovae (which according to S. van den Bergh and M. Peimbert are ejected from the star before its explosion) are also included. The discussion of this problem permits to confirm again the idea that there is a very close similarity between supernovae and novae. To be more exact there are reasons to suggest that supernovae as well as novae are double star systems, that they are relatively 'old', that they are quite peculiar objects and that they are not the final stage of evolution of 'normal' stars.

1. Introduction

When describing the data on supernovae and novae we should concentrate our attention on the problems which have direct relation to stellar evolution. These problems are the following:

(a) During the explosion of a supernova we deal with a violent process which is accompanied by the ejection of gases from the relatively *deep* regions of a star. Thus analysing the explosion we have a unique and extremely important opportunity to obtain some information about the chemical composition of these deep regions. Especially interesting are the objects which correspond to the *late* stages of stellar evolution, because in this case we hope to study directly the chemical composition of the internal parts of stars after long series of thermonuclear processes. According to current ideas these objects are type I supernovae, though other types of supernovae are also of great interest.

Here we have two possibilities: (1) The analysis of the chemical composition of a supernova for the moments not very remote from light maximum $t_{\max}$, the moment $t_{\max}$ is included. (2) The analysis of the chemical composition of supernova remnants. However there is the following difficulty in this method. We have in mind the fact that these remnants very often sweep up a significant amount of interstellar gases (for example van den Bergh (1971b)) and therefore the observed optical spectra of these remnants are from two non-distinguishable sources. There is also another difficulty, connected with the pre-supernova 'activity', suggested by van den Bergh (1971a), Peimbert and van den Bergh (1971), and van den Bergh (1973); see Section 3 of this paper.

(b) The second problem is that we should try to give an answer to the question,

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whether the supernova phenomenon is inherent to the 'normal' stellar evolution (at a certain stage) or whether supernovae are some peculiar objects in the Universe, similar to novae which constitute quite a distinct group of stars on the HR diagram. Besides we should try to give an answer to the general question why supernovae and novae explode.

2. The Chemical Composition of the Envelopes of Supernovae and Novae Close to Light Maximum

There are different types of supernovae, see Zwicky (1964). But we shall speak mostly about type I and type II supernovae. Our information about types III, IV, V supernovae is very limited.

2.1. TYPE I SUPERNOVAE

A typical light curve of these supernovae is shown in Figure 1, taken from the paper of Zwicky (1964). A peculiar property of this curve is the relatively steep drop in brightness during the first 30–40 days after light maximum. Afterwards the brightness of the supernova decreases much more slowly. It is possible that this drop is due to a rapid decrease of temperature of the supernova after the moment $t_{\max}$. Observations show that this decrease of temperature (manifested for example in the growth of magnitudes $B-V$ and $U-B$) is quite large and takes place approximately during the *same* period of 30–40 days; see papers by Pskowskij (1970), Barbon *et al.* (1973), and Mustel (1974).

As usual the principal source of our information about the chemical composition of stars and their envelopes is the analysis of the spectra of these objects. At present there is a more or less general opinion that the spectra of type I supernovae are mostly *absorption* spectra with very wide absorption lines and with heavy blends of neighbouring absorption lines; see Pskowskij (1968), Mustel (1972), Branch and Patchett (1973), Kirshner *et al.* (1973), Mustel and Chugay (1974), and Mustel (1974). All the absorption lines in the spectrum of a particular supernova are strongly displaced towards shorter wave-lengths and show the *same* Doppler displacement:

$$\varkappa = \frac{\Delta\lambda}{\lambda} = \frac{V}{c} \tag{1}$$

in all the spectral regions.

Velocities V inferred from the analysis of the spectra are different for different type I supernovae and are from 6000 to 15000 km s^{-1}.

It is not excluded that strong absorption lines in the spectra of type I supernovae are accompanied by some emission, the same as in the spectra of P Cygni stars; see Kirshner *et al.* (1973). However all the available data show that these emissions are rather weak; see Mustel and Chugay (1974), Mustel (1974). Thus they can hardly influence significantly the results of the chemical analysis of the envelopes of type I supernovae. Moreover in order to eliminate the influence of emission components

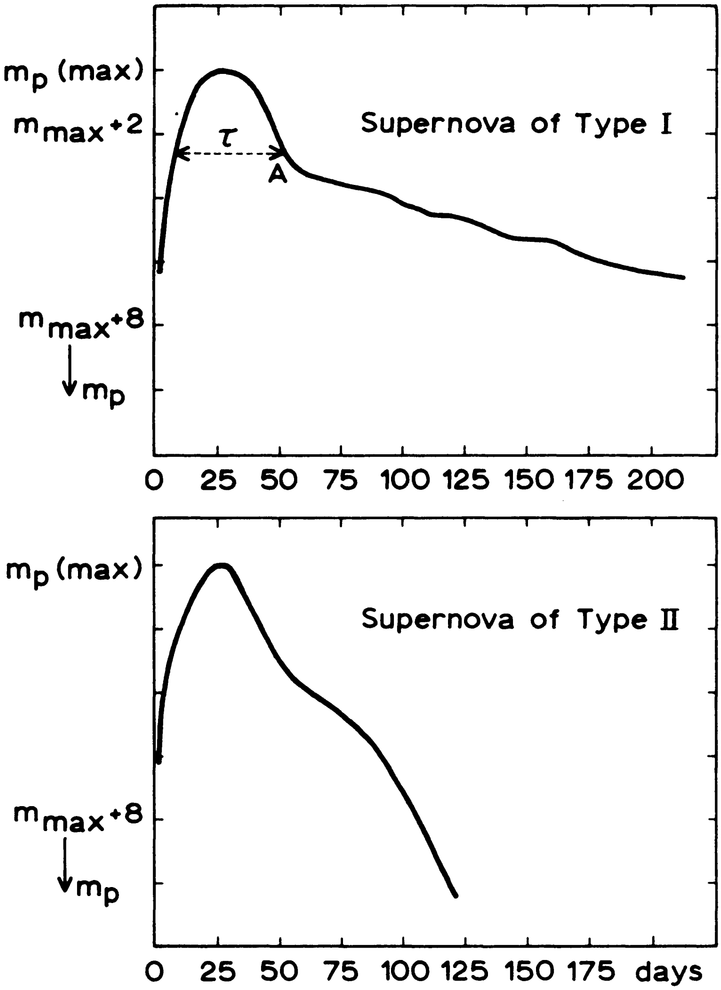

Fig. 1. Light curves of type I and type II supernovae according to Zwicky (1964).

we may use only the short wave-length halves of the profiles of the absorption lines. And generally speaking it is necessary to point out that at present we cannot require too much from the chemical analysis of the envelopes of type I supernovae. In fact the absorption lines in the spectra of these stars are extremely wide, 30–100 times wider than the same absorption lines in the spectra of common novae. Due to this the effects of blending of the neighbouring spectral lines are extremely strong and as a result of this there are only a few absorption lines in the spectra of typical type I supernovae which are relatively free of the effects of blending. Then, there are all reasons to think that this very large width of the absorption lines is due to the presence of a very large velocity gradient in the envelopes of supernovae. Therefore we must elaborate a special and very complex theory of a model of the envelope with a strong velocity gradient. At last we should mention that the strong blending of absorption lines is accompanied usually by another effect. Namely it is very difficult in this case to draw the line of the continuous spectrum.

Thus at present the chemical analysis of envelopes of type I supernovae may be only a semi-quantitative one. We may identify the spectral lines belonging to different elements, to decide what elements are present or absent in these envelopes and in certain cases to give semi-quantitative estimates for the relative abundances of elements. Correspondingly we shall present the results of such a semi-quantitative analysis for the envelope of the type I supernova 1972e in NGC 5253; see Mustel (1973). This analysis is based on a large number of absolute spectral energy distributions published in the paper by Kirshner *et al.* (1973). These distributions were obtained in the range of the spectrum from 3200 to 11 000 Å. The identification of the absorption lines in the spectral energy distributions is given in Figure 2a and Figure 2b of the present paper. This identification takes into account the principal properties of time-evolution of the spectra of type I supernovae, Mustel (1972). The identifications – all vertical lines in Figures 2a and 2b – are carried out for the Doppler factor $\varkappa = -0.035$, i.e. for $V \simeq 10500$ km s^{-1}. The thin vertical lines indicate the calculated positions of individual spectral lines; the dashed vertical lines indicate the outer boundaries of the strongest blends of metals, mostly of Fe II (blends μ, τ, multiplet M73). The dotted vertical lines 'a' indicate the calculated positions of Hα, Hβ, Hγ hydrogen absorption lines; the vertical dotted lines 'e' indicate the normal wave-lengths of Hα, Hβ, Hγ. It is supposed that these normal wave-lengths should correspond to the centres of emissions.

The most important absorptions in Figures 2a and 2b are the following:

2.1.1. *The Absorption Lines of Metals the Lower Atomic Levels of which are ground or metastable*

Generally the effect of metastability of the lower atomic levels plays a very important role in the spectra of type I supernovae. The strongest metallic lines are the lines of Ca II, namely H, K-lines and three lines of the infrared multiplet N2 (their blend) with $\lambda_0 \simeq 8580$ Å. A very important role in these spectra belongs to the absorption lines of Fe II and their blends.

A very prominent absorption in the spectra of type I supernovae at light maximum is due to the blend of two strong lines of Si II, multiplet N2, $\lambda_0 \simeq 6355$ Å. This blend is accompanied by two absorptions of Si II of multiplets NN 3, 4*. After light maximum all these absorption lines of Si II weaken rapidly due to a drop of temperature of the supernova after light maximum and because the lower levels producing these lines are not metastable.

The spectrum of the supernova 1972e contains also absorption lines of Mg II, Sc II, S II. Undoubtedly the spectra of type I supernovae should contain practically all the sufficiently strong absorption lines of metals which are present in the spectra of 'normal' stars, but they are not recognizable due to the strong effects of blending.

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* The lines of multiplets NN 1, 5 of Si II coincide with the blends of other elements.

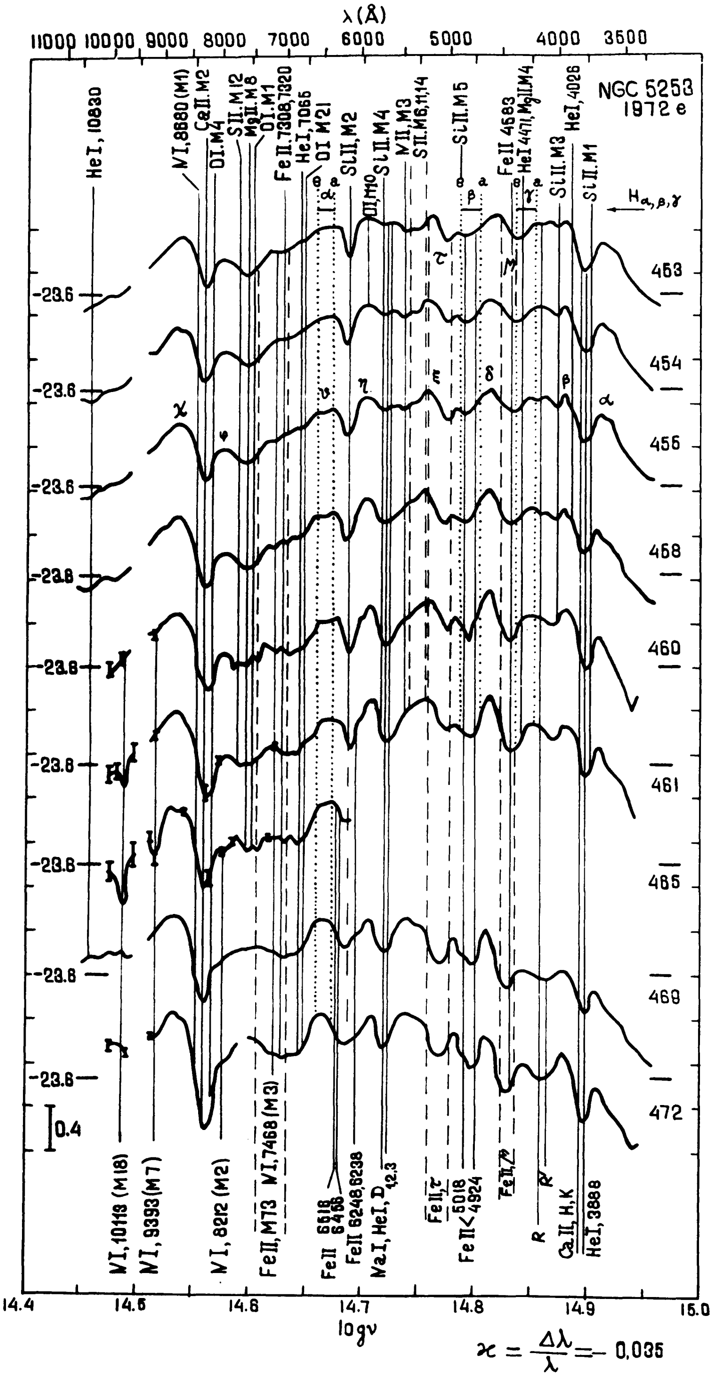

Fig. 2a–b. Identification of absorptions in the spectra of type I supernova 1972e in NGC 5253 according to Mustel (1973). The absolute spectral energy distributions are taken from the paper of Kirshner *et al.* (1973).

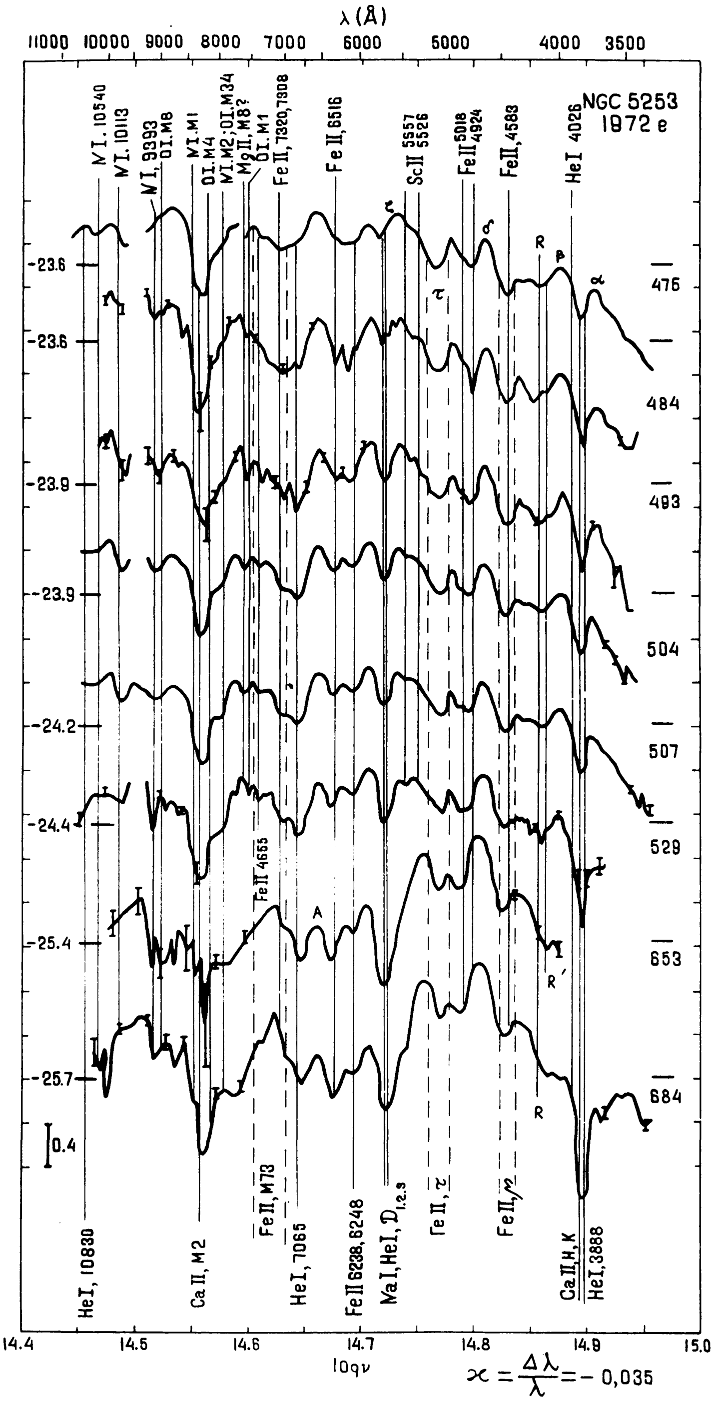
λ (Å)
11000 10000 9000 8000 7000 6000 5000 4000 3500
NGC 5253
1972 e
NI, 10540
NI, 10113
NI, 9393
OI, M8
NI, M1
OI, M4
NI, M2; OI, M34
MgII, M8?
OI, M1
FeII, 7320, 7308
FeII, 6516
ScII 5557 5526
FeII 5018 4924
FeII, 4583
HeI 4026
-23.6
-23.6
-23.9
-23.9
-24.2
-24.4
-25.4
-25.7
0.4
476
484
493
504
507
529
653
684
ζ
σ
τ
R
β
α
A
R′
R
FeII 4665
HeI, 10830
CaII, M2
FeII, M73
HeI, 7065
FeII 6238, 6248
NaI, HeI, D1,2,3
FeII, τ
FeII, ρ
CaII H, K
HeI, 3888
14.4 14.5 14.6 14.7 14.8 14.9 15.0
log ν
$x = \frac{\Delta\lambda}{\lambda} = -0,035$

Fig. 2b.

However in the spectrum of supernova 1966j in NGC 3198 with the unusually narrow absorption lines we may record many of these lines, see Mustel (1974).

2.1.2. *Absorption Lines of* He

At first we have to mention an absorption with $\lambda \simeq 5700$ Å which may be attributed to the line of He I D_3, $\lambda_0 = 5875$ Å. This absorption may be attributed partly to the lines $D_{1,2}$ Na I. Nevertheless there are some arguments, which show that the contribution of the helium line D_3 to this absorption is more important, see Mustel (1974).

It seems that an absorption at $\lambda \simeq 6800$ Å is due to the He I line with $\lambda_0 = 7065$ Å. During the first stages of evolution this line was even a little stronger than the D_3-line, though for two last moments on Figure 2b the line D_3 was already stronger than the line $\lambda_0 = 7065$ Å. There are different possible explanations to these alterations in the relative strength of two He I-lines, including for example some uncertainty in the interpolation of the line of the continuous spectrum.

The situation with the strong He I-line with $\lambda_0 = 10830$ Å is a little uncertain because this line is at the end of the observable spectrum. Besides it may be suggested that the weakness of the *absorption* line of He I 10830 Å may be due to some *emission* within the same line. Such a line-emission may be also responsible for the inequality $W_\lambda(D_3) < W_\lambda(7065$ Å$)$ which was mentioned above. At last we may indicate the following possibility. There are reasons to state (Mustel, 1974) that the strongest excitation of He I-lines takes place in the *inner* parts of the expanding envelope. But in the infrared region of the spectra of supernovae there are many overlapping absorption lines of other elements which may originate in the *outer* parts of the envelope. This more or less continuous absorption may weaken considerably (for the observer) the radiation from He I 10830 Å-line.

2.1.3. *Absorption Lines of* C, N, O

The next very important group of elements includes C, N, O. In the optical parts of the spectrum the strongest lines of these elements coincide with the blends of metals and cannot be identified. Only one exclusion is the line of N II, multiplet 3, $\bar{\lambda}_0 = 5680$ Å. This line was observed during the first moments when the temperature of the supernova was sufficiently high and during the last two moments in Figure 2b when the temperature was *again* sufficiently high, see above.

An analysis* of all the atomic transitions which produce sufficiently strong infrared absorption lines of C I, N I, O I in the spectra of 'normal' stars and a comparison of the results of the analysis with observations (Figures 2a and 2b) permitted us to conclude that nitrogen is a much more abundant element than carbon and oxygen. The strongest lines of N I on 2a and 2b which are sufficiently free from overlapping with other lines and blends are the following: 8212 (M2), 9393 (M7), 10113

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* The oscillator strengths are taken from Wiese *et al.* (1966) and computations are carried out for the excitation temperature $T_{\mathrm{exc}} = 10000°$.

(M18). These lines were prominent also in the spectrum of the type I supernova 1971i in NGC 5055.

On the other hand the identification of those absorption lines of C and O which are usually expected to be strong is difficult. In particular some strong lines of C I, λ_0 9406 M9 and λ_0 8335 M10, may be identified with the absorptions which are ascribed to the strong N I lines. But in this case some other C I lines which are expected to be even stronger than the lines $\lambda_0\lambda_0$9406 and 8335 are practically absent. The same is true for the absorption lines of O I. For example it is expected that the line O I, M10 should be rather strong, but observations do not confirm its existence, see Figure 2a. This conclusion about the very high abundance of N-atoms in comparison with the abundance of C, O-atoms in the envelopes of type I supernovae is in agreement with the computations of Caughlan and Fowler (1962) for the CNO bi-cycle in stars.

2.1.4. *Hydrogen Lines*

Let us consider the spectrum (energy distribution) for the moment JD=2441465 (Figure 2a). This spectrum shows strong absorption lines of N I but no Hα-absorption line for this moment. At the same time the conditions for the appearance of Hα-line are equally favourable. In fact hydrogen and nitrogen atoms have approximately the same ionization potentials; the excitation potentials for Hα and for the lines of N I (9393 and 10113 Å) are also approximately the same. And the mechanism of widening of absorption lines of N I and H is also the same*; see the article of Mustel and Chugay (1974). Thus we may conclude that the abundance of hydrogen is much lower than the abundance of nitrogen. In addition we may say that Figures 2a and 2b do not show any emission bands of Balmer series.

Now let us summarize our discussion. The presence of sufficiently intense absorption lines of He I and the very high excitation potentials of the corresponding atomic transitions speak in favour of the conclusion that helium is the most abundant element in the envelopes of type I supernovae. It seems that the next element is nitrogen. But further studies are needed to obtain more definite data about the relative chemical composition of envelopes of type I supernovae.

2.2. TYPE II SUPERNOVAE

Type II supernovae are in many respects similar to common Novae. At first we may point out a similarity between the light curve of these supernovae and the light curves of certain novae, especially the 'fast' ones. The spectra of type II supernovae are similar in many respects to the spectra of the 'fast' novae. These supernova spectra contain absorption lines with the accompanying emission at the redward side of absorptions. The evolution of the spectra of these both objects is also similar. At light maximum the emissions are relatively weak but later their intensity steadily increases whereas the absorption lines fade away. The spectra of type II supernovae

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* The velocity gradient.

differ markedly from the spectra of type I supernovae. For example they contain rather strong absorption and emission lines of *hydrogen*.

According to available information the velocities of the expansion of envelopes of type II supernovae are on the average somewhat lower than the velocities of the expansion of envelopes of type I supernovae.

The problem of time-evolution of the spectra of type II supernovae is very complex. It seems that we should consider separately the spectrum created by the ejected envelope itself and the spectrum emitted by the 'central remnant' of the supernova, see paper of Mustel (1974). Then it is very interesting to note that in the spectra of the type II supernova 1969l in NGC 1058 there was a progressive drift with time toward the red of all the absorption and emission features, see Ciatti *et al.* (1971). After light maximum the mean expansion velocity was decreasing during two months from $V \simeq 9500$ km s^{-1} to 5500 km s^{-1}.

There is no quantitative chemical analysis of the envelopes of type II supernovae. We may mention only the elements which were definitely identified by several investigators: H, He, O, N, Fe; Ca and some other elements. However the relative abundances of all these elements are not known. We may mention also the results of Branch and Greenstein (1971) obtained for a type V supernova 1961 in NGC 1058. These authors find that the chemical composition of ejected material may be similar to that of the Sun, except for a deficiency of hydrogen. However it is not yet clear if the type V supernovae should be classified as supernovae; van den Bergh (1973).

As to the chemical composition of the outer layers of novae we may refer to paper of Antipova (1974). The available data show the following anomaly: in comparison with the 'normal' stars there is a noticeable overabundance of N, C, O in the envelopes of Novae, whereas the relative abundances of metals are practically identical to those in the atmospheres of 'normal' stars. It seems that there is no anomaly in hydrogen.

2.3. THE CHEMICAL COMPOSITION OF SUPERNOVA REMNANTS AND THE ACTIVITY OF SUPERNOVAE AND NOVAE BEFORE EXPLOSION

When speaking about the supernova remnants we have to include in this conception not only the gaseous envelope ejected during the explosion but also other components. To be more exact we may speak about the following components: (A) The gases which are ejected from the star *during* a relatively short explosion and which constitute the principal envelope of the supernova at light maximum and during some period after it up to the moment when this envelope begins to interact with other components. (B) The circumstellar shells around supernovae which according to the suggestion of van den Bergh (1971a) are ejected from the star before the explosion. (C) The interstellar medium (gases and dust) in the space around supernovae.

Let us consider shortly the first two components. The third component C does not belong to the supernovae themselves and we shall mention its influence only in the cases when this component plays an important role in the physics of the supernova remnants.

2.3.1. *The Envelope Ejected During the Explosion of the Supernova*

This envelope is usually a source of optical and radio emission. As to the optical emission we should like to point out the following circumstances which are important in the interpretation of the optical emissions from component A of type I supernovae. We have in mind the conclusion about the presence of a very large velocity gradient inside the envelopes of these stars; see Section 2 of this article. Due to the velocity gradient the line emission will occupy a very large frequency interval and this will strongly weaken the optical line-emissions. It seems that this is one of the main reasons why the recognition of the optical emissions from the remnants of Tycho's and Kepler's supernovae is so difficult. In particular it may be suggested that Hα-emission from the faint long filaments of Tycho's remnant is due to the presence of component C in the parent envelope of the supernova. In fact according to van den Bergh (1971b) the expanding shell of Tycho's supernova has swept up a mass of *interstellar* gas that is several times greater than its own mass.

Approximately the same situation is true for Kepler's remnant. There is no optical emission from component A in this case. At the same time we know that the radio-emission from the supernova remnants is continuous and therefore the influence of even a very strong velocity gradient here is practically absent. The Kepler's remnant is a fairly thick shell source* with a shell thickness-to-radius ratio of about 0.5, see Herman and Dickel (1973). On the basis of radio observations carried out by Hazard and Sutton (1971), it may be computed that the expansion velocity of the remnant is approximately 12000 km s^{-1}; see van den Bergh (1973).

Thus we may conclude that unfortunately now we do not have any definite information about the chemical composition of component A of both Tycho's and Kepler's type I supernova remnants.

As to the bright radio source Cas A which is connected with a type II supernova the observations show that the fast moving knots of this remnant which certainly belong to component A, exhibit emission lines of [O I], [O III], [S II] and [Ar III]. In these knots oxygen, argon and sulphur are overabundant in respect to hydrogen and nitrogen by at least a factor of 30. This shows that the bright knots in Cas A could not have swept up a significant amount of (hydrogen-rich) interstellar material; see van den Bergh (1973).

We shall not speak here about the Crab Nebula since we do not know what type of supernovae produced this remnant. The information about the abundance of hydrogen in this nebula is somewhat uncertain; see again van den Bergh (1973).

2.3.2. *Circumstellar Shells Around Supernovae*

It is known that in addition to the usual fast moving gases (component A) certain supernova remnants reveal some quasistationary or relatively slow moving gases in

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* This is probably the influence of the velocity gradient and the absence of a dense interstellar medium in the vicinity of the supernova.

the form of bright knots and filaments. These formations – component B – are observed in the radio source Cas A and in the remnant of Kepler's supernova. The main properties of these knots and filaments are the following: (a) relatively small velocities, much smaller than the average velocity of component A; (b) there is practically no correlation of these knots and filaments with the radio shells and generally with component A. For Kepler's remnant this lack of correlation is pointed out by Herman and Dickel (1973); (c) these knots and filaments have anomalously high intensity of forbidden emissions $\lambda_0\lambda_0$6548, 6584 Å of N II. Analysing this last property of component B for the radio source Cas A, van den Bergh (1973) writes: "For temperatures $T > 6200$ K Peimbert and van den Bergh (1971) find that the nitrogen-to-oxygen ratio in the quasi-stationary flocculi in Cas A is higher than that prevailing in the Orion nebula. Taken at face value this result implies that the quasi-stationary flocculi cannot represent interstellar gas that was trapped by the expanding supernova shell. The observed overabundance of nitrogen might be understood by assuming that the flocculi were formed by the compression of a pre-existing circumstellar shell. Such a shell might have been enriched in ^{14}N that was produced in the CNO bi-cycle (Fowler and Caughlan, 1962)."

We may notice that this conclusion (which may be applied to the case of Kepler's remnant) is in agreement with the conclusions of Mustel (1973) about the very important role of N-atoms in the *internal* parts of supernovae, see Section 2 of this paper, though the sources of gases in both these cases are different. It seems that the gases which produce B-component are ejected from some subphotospheric levels of the star whereas the component A is produced by the gases which are localized much closer to the center of the supernova. It seems that the important role of N-lines in the spectra of both components shows that the number of N-atoms is enhanced practically at all levels inside the star before its explosion.

All the three points (a), (b), (c) enumerated above do confirm the idea of van den Bergh and Peimbert that there is some ejection of gases from the more or less *deep regions* of supernova before its explosion and that this process may take place during a relatively long period of time. It is difficult to expect that component B is produced by a simple compression of interstellar gases after the supernova explosion. If it would be so then the B-component in Tycho's remnant had to be much more prominent than that in the case of Kepler's remnant. In fact Kepler's remnant is located at a height $Z = 1.4$ kpc above the galactic plane. At the same time we have already mentioned that the interstellar gases played a very important role in the case of Tycho's remnant, see again van den Bergh (1971b).

There are some other very interesting considerations which support the idea that supernovae and novae are the sources of a more or less continuous activity before their explosions. It seems that this activity (at least for novae) is continuing even after the explosion.

In his paper Weaver (1974) presented a model of the envelope around nova V603 Aql 1918. According to this model 'the equatorial' parts ('rings') of the envelope are the result of an interaction of gases ejected during the explosion with the gases ejected before the explosion. This conclusion is based on the results of Kraft (1959) according to which DQ Her even after its explosion possesses some small rather dense emitting disk* (or ring), this disk is moving together with the post nova itself along the orbit of the double system. And it is quite natural to suppose that this disk (or ring) is due to the interactions between the two components in this double system.

Thus it may be supposed that not only after the explosion of the star but also *before* it the nova is surrounded by a 'circumstellar' envelope – component B – according to the previous terminology.

The equatorial belt (or ring) in the envelopes of V603 Aql and DQ Her was discussed in detail by Mustel and Boyarchuk (1970). The principal properties of the envelopes around the post-novae outlined in the above paper were recently confirmed in the papers of Malakpur (1973) and Hutchings (1972). Thus it seems that the presence of these belts (or rings) is an invariable property of the envelopes around *all* novae.

The 'belts' (or 'rings') in the envelopes around post novae produce certain emission components – intensity maxima – in the spectra of these objects. And it is very important to note that the most characteristic property of these 'belts' or 'rings' is the presence of *strong* emissions due to the same forbidden lines $\lambda_0\lambda_0 6548$, 6584 Å of [N II]! In particular the 'equatorial belt' in the envelope around DQ Her was observed *only* in these lines of [N II], see Mustel and Boyarchuk (1970). A very long persistance of the lines of [N II] in the spectrum of the equatorial 'rings' in the envelope of V603 Aql was pointed by Wyse (1939). Thus we have serious reasons to consider that in the case of novae we have also a continuous ejection of gases from the relatively deep regions of the star which are enriched in ^{14}N.

It seems that this similarity between novae and supernovae is very significant; see Mustel (1970b). It supports strongly the idea that the supernovae are also double star systems. Now there are reasons to think that novae are relatively 'old' objects, see for example Kukarkin (1970, 1973). Therefore a similarity between novae and supernovae may speak in favour of the hypothesis that the supernovae are also relatively 'old' objects. This hypothesis is confirmed by a relatively high abundance of N in the envelopes of type I supernovae and by the absence of hydrogen in these envelopes, see above. Moreover since novae form a somewhat peculiar and isolated group of stars we may suggest that supernovae are also quite peculiar objects and are not the final stage of 'normal' stars at the end of their evolution. All these problems are going to be discussed by the author in *The Astronomical Journal of the U.S.S.R.* in the nearest future.

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* We do not speak here about a very extensive envelope which is distant from the post nova.

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