required to kill the tumor while in the case of neutron rays only $\frac{750}{260} = 2.9$ times the mouse lethal dose produces the same tumor effect. This comparison of dosage ratios indicates that neutron rays may be more selective than x-rays in their effects on this tumor.

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CHARACTERISTIC TEMPERATURES IN SUPER-NOVAE

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A. Introduction.—Some time ago Baade and I called attention to the existence of certain temporary and extremely luminous objects in extragalactic nebulae.[1] We suggested:

1. These temporary objects are *individual stars* which behave like giant analogues of common novae and which, therefore, may appropriately be called super-novae.
2. The visual brightness of super-novae, on the average, is comparable to the brightness of the nebulae themselves.
3. The average frequency of occurrence of super-novae is one per extragalactic nebula per several centuries.

Recently the above suggestions have been verified to a great extent. A thorough investigation of past photographic records of temporary objects in nebulae by Baade, as well as the discovery in January, 1936, of a super-nova in N. G. C. 4273 have contributed much new evidence toward the verification of our *super-nova hypothesis*. It has also proved possible to establish between certain physical characteristics of temporary stars a number of relations which enable us to satisfactorily bridge the gap between common novae and super-novae.[2]

In addition to the three mentioned postulates Baade and I advanced some preliminary calculations concerning certain specific properties of super-novae. From these calculations it follows that the knowledge of the total energy E_t liberated in a super-nova outburst would throw much light on a number of fundamental astronomical problems. For a satisfactory determination of E_t a fairly accurate knowledge of the distribution of equivalent temperatures (or rather of the radiation density) throughout exploding stars is necessary. Although no detailed calculations are as yet possible, I wish to communicate here some qualitative estimates which may prove helpful in clearing up certain difficulties which have recently been voiced by C. Payne-Gaposchkin.[3]

In order to fix our ideas it is advantageous to visualize two critical surfaces in a super-nova. The first surface, which we shall call the *boundary surface* Σ_b is defined by the outermost layers ejected from the nova. The second surface we may call the *surface of separation* Σ_s ("Ablösungsfläche" in German would be most descriptive). This surface defines the demarkation between the gases which are ejected into interstellar space and that matter which remains with the central star. Since in the late stages of a nova outburst this demarkation will not be unambiguous, we define Σ_s as the *smallest* surface which contains *most* of the matter remaining with the star. The dimensions of both Σ_b and Σ_s change in time. It will also be noticed that the physical conditions on neither of the two surfaces are accessible to direct observation. Only during the later stages of the outburst Σ_s becomes identical with the surface of the central star and may be observed directly. It must be pointed out in particular that no meaning can be attached to such a notion as the temperature of Σ_b, since physical conditions which prevail in the neighborhood of this surface are certainly far different from any thermal equilibrium. On the other hand it would seem permissible to talk about the temperature T_s at the surface of separation. Conditions near Σ_s can probably be approximated by a suitably chosen state of thermal equilibrium. During the later stages the physical conditions near Σ_s will be analogous to those on the surface of an ordinary very hot star. We shall primarily be concerned with the thermal conditions on Σ_s.

For simplicity we assume that Σ_s is a sphere whose radius R_s does not exceed 10^{13} cm., an estimate which would seem conservative even if the original star involved in a super-novae outburst is a super-giant star. From the fact that super-novae have appeared in unresolved neighboring nebulae such as N. G. C. 5253 we know that the absolute magnitude of the original star may in fact be fainter than $M = -1$.

B. First Estimate of T_s.—We notice first that the total energy E_t which is liberated during the nova outburst is greater than the energy E_{vis} which is radiated in the form of visible light. It is necessarily $E_t > E_{\text{vis}}$ because

E_t, in addition to E_{vis}, contains the energy of the invisible radiation, as well as the kinetic and potential energies of the ejected gases. At the beginning of the outburst, that is, a few days before maximum luminosity, E_t must have been present as radiation of the temperature T_s, trapped in a relatively thin shell of the volume V around Σ_s. We therefore have for the density u_s of the radiation at Σ_s

$$u_s = aT_s^4 = E_t/V \gg 3E_t/4\pi R_s^3 > 3E_{\text{vis}}/4\pi R_s^3 \qquad (1)$$

where $a = 7.63 \times 10^{-15}$ ergs/cm.^{3} deg.^{4} We write $R_s = r_s \times 10^{13}$ cm. For the super-nova S-Andromedae it is approximately $E_{\text{vis}} = 1.2 \times 10^{48}$ ergs and therefore

$$T_s > 4.4 \times 10^5/r_s^{3/4}. \qquad (2)$$

C. Second Estimate of T_s.—A lower limit for the total mass M of the ejected gases may be obtained in several ways. The most direct method is perhaps the following.

We consider a spherical shell of gas of radius R which is expanding with the velocity $v = dR/dt$. Every column of unit cross-section is acted upon by the radiation pressure p. From the law of conservation of energy we then have

$$Mdv/dt = 4\pi R^2 p. \qquad (3)$$

If L_i is the radiation which impinges on the inside of the shell it is approximately

$$p_i = L_i/4\pi R^2 c \qquad (4)$$

where c is the velocity of light. Therefore

$$Mdv/dt = L_i/c. \qquad (5)$$

As a lowest estimate for L_i we may assume $L_i = 4L_{\text{vis}}$ since for every visible photon there is present one ultra-violet photon whose energy is at least three times as great (in the case of hydrogen). Inasmuch as a considerable amount of resonance radiation must be trapped inside of the shell we really have $L_i \gg 4L_{\text{vis}}$. Consequently

$$M \gg 4L_{\text{vis}}/(cdv/dt). \qquad (6)$$

We apply this relation to the later stages of the recent and best investigated super-nova in N. G. C. 4273. This object, twenty to fifty days after maximum, had a luminosity corresponding to $L_{\text{vis}} = 2.3 \times 10^{40}$ ergs/sec. No acceleration of the shell could be detected during this period, so that, taking into account the observational uncertainties, $dv/dt < 10$ cm. sec.$^{-2}$ and consequently from (6)

$$M \gg 3.2 \times 10^{29} \text{ gr.} \qquad (7)$$

We are therefore safe in assuming that the total mass of the ejected gases in the case of the mentioned super-nova is not less than $M = 10^{30}$ gr.

We now turn around and apply (3) to the earliest stages of the super-nova outburst during which, in a few days, the shell is brought to a velocity of the order of 7×10^8 cm. sec.$^{-1}$. This implies that the acceleration at the earliest stage must have been of the order 10^4 cm. sec.$^{-2}$ or more. Consequently, according to (3), the light pressure on Σ_s during the early stages is of the order

$$p > 10^7/r_s^2 \text{ dynes cm.}^{-2}. \tag{8}$$

Putting the radiation density $u_s = aT_s^4$, $R_s = 10^{13} \times r_s$ and $u_s/6 < p_s < u_s/3$ we get

$$T_s > 2.5 \times 10^5/r_s^{1/2}. \tag{9}$$

Since the super-nova in question is a considerably smaller object than S-Andromedae our second estimate of T_s is in good agreement with (2).

We also call attention to the fact that from the above considerations we may derive a lower limit for the kinetic energy E_k of the gases ejected from the super-nova in N. G. C. 4273. It is

$$E_k = Mv^2/2 \gg 2.5 \times 10^{47} \text{ ergs} \tag{10}$$

and therefore

$$E_k \gg E_{\text{vis}} = 6.7 \times 10^{46} \text{ ergs}. \tag{11}$$

This result verifies our original suggestion that E_{vis} is by no means the most important loss of energy from a super-nova as has recently been claimed by Mrs. C. Payne-Gaposchkin.

D. Third Possible Estimate of T_s.—According to Zanstra's theory of nebular envelopes the difference Δm in luminosity of the central star and the gaseous shell is a measure of the temperature of the central star. It is not possible as yet to apply this method to the determination of T_s in any super-nova. Since no continuous spectrum could be detected in the light of the most recent super-nova in N. G. C. 4273 it follows that the temperature of the central star must have been very high indeed. It would in fact be very surprising if T_s should be lower for super-novae than for ordinary novae for whose central stars temperatures of the order of 150,000 degrees have been found. It will however be of great importance to search for super-novae in "nearby" extragalactic systems for which Δm and consequently T_s may actually be determined directly.

E. The Total Energy E_t Liberated in Super-Novae.—As already mentioned, E_{vis} constitutes but a small part of E_t. Other energies which contribute materially to E_t are

1. Invisible radiations.
2. The kinetic energy of the ejected gases.
3. The gravitational potential energy of the ejected gases.
4. The electric potential energy, caused by the separation of oppositely charged gaseous clouds. The subsequent breakdown of these potentials plays an essential rôle in the *generation of cosmic rays* from super-novae.
5. The heat content of the central star.

From simple theoretical considerations as well as from the analysis of the observational data, it follows that the ratio E_t/E_{vis} increases rapidly with increasing absolute luminosity of a nova. An account of these considerations will be published in another place.

F. Final Remarks.—The estimates given in this paper for the surface temperatures T_s of the central star in a super-nova confirm the general correctness of the calculations communicated by Baade and myself in our original paper (first limiting case of this paper). We there also suggested (second case) that the radiation coming directly from the outermost layers of the expanding gaseous envelope does not necessarily contain an excessive amount of ultra-violet radiation, and in this sense its effective temperature T_b may be *low.* From this, however, it does not follow that the total energy liberated is $E_t = E_{\text{vis}}$ as has been argued by C. Payne-Gaposchkin[3] who failed to make the obvious and necessary distinction between the two surfaces Σ_b and Σ_s. It also seems ill advised to conclude anything regarding the distribution of temperature in super-novae from the character of their visible spectra as long as a satisfactory explanation of some of the most important features of these spectra is completely lacking. In view of the meager data available at the present it will be advisable to await more observational data on super-novae before embarking on any too elaborate theories concerning these interesting objects.

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