ON THE PHYSICAL CONDITION OF THE SUPERNOVAE

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There seems to be good evidence for the existence of a group of novae that are several magnitudes brighter absolutely than the galactic novae commonly observed. They have been called the supernovae. According to Baade and Zwicky,[1] who have assembled the evidence, they attain absolute visual magnitude -13 at maximum, with a small dispersion; this estimate is apparently based on a value of -14.7 for the absolute visual magnitude of the average galaxy. If the Harvard value[2] $-14.5_{pg} \equiv -15.4_{vis}$ is adopted for the absolute magnitude of an average galaxy, the absolute visual magnitude of an average supernova becomes -13.7. Thus the supernova S Andromedae, which, on the basis of $22^{m}.2$ for the distance modulus of the Andromeda nebula, had at maximum an absolute visual magnitude -14.7, was not far from typical in luminosity. Calculations based upon its relatively well observed light curve are probably reasonably representative, giving values for the radiated light and energy that are perhaps greater than the average by a factor of two.

At a time when the spectra of supernovae were unknown or enigmatic, it was reasonable, as suggested by Baade and Zwicky,[1] to assume that the conditions that produced them differed greatly from those that produce the spectra of the normal novae. At present, however, it has been shown that four of the supernovae differed spectroscopically from the normal novae essentially only in the radial velocities of the ejection of material. The spectra of S Andromedae[3] and Z Centauri[4] were recently shown to have consisted of wide bright lines and a continuous background; the latter star, at least, had a strong wide band at 4650, as well as indications of the presence of the Balmer lines.[5] A similar deduction had previously been made by Vorontsov-Velyaminov,[6] who classified the spectrum of Z Centauri as O. More recently the spectra of two supernovae obtained at Mount Wilson (in N. G. C. 4273 and N. G. C. 4303) have been published by Humason.[7] Both spectra, while "not easy to interpret," appear to have displayed the lines of hydrogen,[8] and their strongest feature seems, from the figure, to have been a bright band centered near 4650. The spectra are strikingly similar to the spectrum of Z Centauri.[9] From the widths of the bands in the Mount Wilson spectra Humason deduces a radial velocity of expansion of 6000 km./sec. The writer suggested a velocity of the order of 10,000 km./sec. for Z Centauri. The Mount Wilson value will be adopted for purposes of calculation.

It seems legitimate to conclude that the three spectra, of Z Centauri, and of the supernovae in N. G. C. 4273 and in N. G. C. 4303, all contained wide bright lines of hydrogen of moderate strength, and a stronger wide bright band centered near 4650, which probably consisted chiefly of the group of N III lines that are a conspicuous feature of galactic novae at a relatively early stage. In the notation of the Commission on spectral classification of the International Astronomical Union,[10] all three spectra could be described as *Qun!;* they differ from those of galactic novae only in the extreme width of their bright bands. The spectrum of S Andromedae was examined only visually, so that the blue region at 4650 was not well placed for observation. A discussion of the published descriptions leads to the conclusion[3] that the spectrum contained wide bright lines, and we shall assume that S Andromedae was spectroscopically a typical supernova, as it appears to have been typical in light curve[11] and fairly typical in luminosity.

For an ordinary nova, a spectrum of Class *Qu* is associated with a temperature not greater than 30,000°; if the nebular lines N_1 and N_2 of O III are present, they are at least inconspicuous. The temperature of a nova in the nebular stage (*Qy*, *Qz*) is[12] about 50,000°, which must therefore be regarded as an *upper* limit for these three supernovae at the dates on which their spectra were secured, because they had not yet reached Class *Qy* or *Qz*. The available evidence concerning the spectra of novae indicates that the maximal temperatures were probably even lower.[13] It therefore seems that the exceedingly high surface temperatures contemplated by Baade and Zwicky* for the supernovae must be ruled out by observation, and that these extremely bright stars should now be regarded as differing from other novae only in their luminosities and in the velocities of expansion. A few rough calculations will show that in other respects a supernova resembles an ordinary galactic nova.

In what follows we adopt a velocity of expansion 6×10^3 km./sec., a total range of 14 magnitudes (near the minimum value for S Andromedae), a time of rise, t, of two days (of the order accepted by Baade and Zwicky), and a ratio, $\gamma = 10$, of maximal to minimal surface brightness, corresponding to a ratio of about 3 in absolute temperature, probably a maximum value. Then according to the simple relation given by Gaposchkin[14]

$$R_0 = \frac{1}{8}\frac{vt\gamma^{1/2}}{u^{1/2}}$$

where v is the velocity of expansion, u the total range in brightness and R_0 the radius before the outburst. Inserting numerical values we obtain $R_0 = 8R_\odot$, a radius appropriate to a giant star like Capella, with an absolute visual magnitude about zero. If we suppose, therefore, that a supernova has an absolute visual magnitude zero before its outburst, we obtain, with a range of fourteen magnitudes, an absolute visual magnitude at maximum of -14.0, in good agreement with the observed value -13.7, and an independent check on the conditions adopted.

On the basis of the same simple theory we obtain for the maximal radius a value of 1500 times the solar mass—an increase of radius by about 200 times. The proportional increase of radius for normal novae is of the same order.[15] The similarity, of course, results from the fact that the visual ranges of the two types of nova are not very different.

For a radius of 1500 $\odot$ and an absolute visual magnitude -14.7, we should obtain, on the somewhat unlikely assumption of black-body radiation, a temperature of 22,000° by the method used by Baade and Zwicky, a result that confirms our conclusion that the temperature is not excessively high. A value of 22,000° is indeed not unreasonable in view of the ionization temperature of 30,000° deduced shortly after maximum, and of our knowledge of the post-maximum increase of effective and ionization temperatures for other novae.

The large differences between our temperatures and those of Baade and Zwicky (which are of the order of 10^6 degrees) are entirely a consequence of the different adopted maximal radii. In the light of present spectroscopic knowledge there seems little justification for supposing, as they do, that the maximal radii of supernovae are actually *smaller* than those of normal novae. On our view they are *larger* in rough proportion to the radial velocities. From a simple geometrical standpoint, at least, this picture seems acceptable, since with such high velocities, far exceeding the velocity of escape, gravitation can play no part in the motions and ultimate equilibrium of the ejected material; the dimensions finally attained should be governed only by the amount of matter, the speed with which it is ejected, and the energy incident on it from below (for discussion on this point I am indebted to Dr. Fred L. Whipple).

Baade and Zwicky concluded that the mass of the energy sent out by a supernova in the form of radiation may be of the same order as the original mass of the star. But this conclusion is very sensitive to the adopted surface temperature. If the calculations are repeated for maximal temperatures of 13,000°, 20,000°, and 32,000°, we obtain, for the total energy radiated per second by S Andromedae at maximum, 5×10^{41}, 3×10^{42} and 2×10^{43} ergs, respectively. On integrating the light curve, the *total* amounts of energy radiated at these three temperatures (assumed constant) are seen to be 4×10^{46}, 2.5×10^{47} and 1.6×10^{48} ergs, respectively, during the first two months of the star's brightening.** When these quantities of energy are converted into grams, we have, for the total loss of mass by radiation at the three temperatures considered, 5×10^{25}, 3×10^{26} and 2×10^{27} grams, respectively. None of these quantities is significant in comparison with the mass of an ordinary star, such as we suppose the supernova to have been before its outburst. And since the average supernova seems to radiate about half as much light as S Andromedae, the above masses should probably be halved if they are to represent the general case.

It should be noted that the above calculations were based on the assumption, used by Baade and Zwicky, that the nova radiated like a black body. More recent researches on the spectral energy distribution for stars with expanding atmospheres[16] have shown that this assumption can be replaced by a more precise one. But it is unlikely that even when allowance is made for an excess of energy in the ultra-violet portion of the spectrum, the mass of the radiated energy will approach that of the star itself.

The spectra do not lend themselves to quantitative work. One qualitative conclusion can, however, be drawn from them. Their bright bands are about as strong as in the spectra of normal novae at a similar stage; thus it is probable that about the same proportion of the surface is involved in the outburst. The loss of mass, by radiation and ejection, is therefore probably in about the same ratio to the total mass for both sorts of novae.

It seems possible that the supernovae are merely novae that have developed from giant rather than from dwarf stars (it is suggestive in this regard that their dispersion in absolute magnitude at maximum is noted by Baade and Zwicky as small, while it must be larger for "ordinary" novae, if van Maanen's estimate[17] of an absolute magnitude not brighter than zero for Nova Sagittae No. 2 is correct). If so, their frequency (perhaps a millionth of that of normal novae) may well represent the relative commonness of the giant and dwarf stars from which the two types originate.

Summary.—It has recently been shown that the spectra of supernovae display features similar to those of normal galactic novae, but with bright lines that are considerably wider. If it is accordingly assumed that their surface temperatures, a week or two after maximum, are normal for novae, and of the order of 20,000°, we are led to maximal dimensions that are larger than those of galactic novae in rough proportion to the radial velocities (deduced from the widths of the bright lines). The outburst of a supernova thus seems to be a phenomenon that differs only in scale from that of a normal galactic nova. The total energy radiated during an outburst is of the order of 10^{48} ergs, or 10^{27} grams, and if we suppose the star to have had a normal stellar mass before brightening, the loss of mass by radiation is therefore negligible.

* It is an interesting speculation to inquire what kind of spectrum would be given at the temperature of 10^6 degrees mentioned by Baade and Zwicky. The radiation would consist principally of soft x-rays. All the lighter atoms, common in the atmospheres of ordinary stars, would probably be stripped (the corresponding level of ionization is about three thousand volts), and a qualitative guess suggests that the spectrum would show no lines strong enough to be observed in contrast with the continuous spectrum, since the only surviving atoms (those of high atomic number) are cosmically rare.

** Baade and Zwicky considered that the main radiation of energy took place within 25 days of maximum.

[1] Baade and Zwicky, these PROCEEDINGS, **20**, 254 (1934).
[2] Shapley, *Ibid.*, **19**, 594 (1933) (H. Rept. 92).
[3] C. Payne Gaposchkin, *Ap. Jour.*, **83**, 245 (1936).
[4] C. Payne Gaposchkin, *Ibid.*, **83**, 173 (1936).
[5] Johnson, *H. B.* 902 (1936).
[6] Vorontsov-Velyaminov, *Russ. Astr. Journ.*, **8**, 42, 27 (1931); *Astr. Nach.*, **242**, 208 (1931); "New Stars and Galactic Nebulae," 221, 261 (1935).
[7] Humason, *P. A. S. P.*, **48**, 110 (1936).
[8] Humason, loc. cit., p. 112.
[9] *Harv. Ann.*, **76** (37, and Plate 2) (1913); Johnson, loc. cit.
[10] *Trans. Int. Astr. Union*, **1**, 98 (1922).
[11] Lundmark, *Kungl. Vetens. Svensk. Hand.*, **60**, No. 8, 55 (1917).
[12] Vorontsov-Velyaminov, *Zeit. Ap.*, **10**, 365 (1935).
[13] Menzel and Payne, these PROCEEDINGS, **19** (No. 7) (1933); see also F. L. Whipple and C. Payne Gaposchkin, *Harv. Circ.* 412 (1936), for the increase in temperature of Nova Herculis immediately after maximum.
[14] S. Gaposchkin, *Harv. Bul.* 899 (1935).
[15] S. Gaposchkin, *Harv. Bul.* 901 (1935).
[16] Kosirev, *Mon. Not.*, **94**, 430 (1934); F. L. Whipple and C. Payne Gaposchkin, *Harv. Circ.* 413 (1936).
[17] Van Maanen, *P. A. S. P.*, **46**, 282 (1934).

A MODEL IMITATING THE ORIGIN OF SPIRAL WALL STRUCTURE IN CERTAIN PLANT CELLS

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The walls of many plant cells show spiral structure. When a living cell with spiral structure elongates, spiral growth results, accompanied by rotation or twisting of the cell about its principal axis. Spiral growth of this type is particularly evident in the mature sporangiophore of Phycomyces (Oort, '31). No satisfactory explanation has been given for the origin of spiral structure, and hence of spiral growth, in the primary wall of a tubular cell of this type.

Since the steepness of the spiral in the cell of Phycomyces can be experimentally modified during growth (Castle, '36), it appears that spiral structure in the primary, growing wall is not rigidly predetermined, but that it must be due to some kind of equilibrium condition of forces existing at the growing region. Furthermore, it is probable that these forces are exerted on and in the cell wall itself, and that they result from the interaction between outward turgor pressure and elastic forces within the wall. On the assumption that these elastic forces might be concerned in the