implies the more or less symmetrical distribution of variables about the galactic nucleus, the distance to the center of the galaxy is

$$r_c = 9.7 \pm 1.2 \text{ (m. e.)}. \quad (3)$$

The magnitude frequency curve in the area MWF 233, which is somewhat more distant from the galactic center and in lower latitude, does not yield as clear a maximum as appears in MWF 269. The pronounced maximum found some years ago[3] in MWF 185 is at magnitude 15.75, but the absence of galaxies in this low latitude field near the galactic center does not permit the application of the present method.

A special study is now in progress of the variables in those fields on the border of the galactic nucleus in which nebulae are abundantly found. We should be able with the additional material to reduce the mean error of (3) to half the present value.

[1] *Harv. Circ.*, **411**, 3 (1936).

[2] *Harv. Ann.*, **105**, 243 (1936).

[3] Shapley and Swope, these PROCEEDINGS, **14**, 830 (1928).

SUPERNOVAE AND STELLAR COLLISIONS

BY FRED L. WHIPPLE

HARVARD COLLEGE OBSERVATORY

Communicated February 13, 1939

Introduction.—The hypothesis that a nova may origniate from a collision of two stars would long have been favored except for the theoretical rarity of such collisions. Luyten,[1] Jeans[2] and others have calculated that a stellar collision should occur in our Galaxy only once in 10^{13} to 10^7 years, whereas several novae occur each year. William Pickering and Nölke[3] suggested that collisions of stars with bodies of asteroidal or planetary dimensions might be sufficient to set off the explosions.

Supernovae represent a catastrophic phenomenon of far greater magnitude and much smaller frequency than do ordinary novae. Modern estimates of the space densities of stars in the nucleus of the galaxy and in external galaxies indicate much greater values than those of a few years ago. It is the purpose of the present study to show that on the basis of recent data the frequency of stellar collisions can be comparable with the frequency of supernovae, and that the collision hypothesis must be considered in a discussion of the origin of supernovae.

1. *Distribution.*—It is necessary first to study the space distribution of supernovae in the external galaxies with which they have been associated.

Table 1 contains, in the eighth column, the apparent distance (r in parsecs) from the nucleus of the galaxy to the supernova for each of the twenty well-authenticated supernovae occurring outside our system. The distance has in each case been corrected (to r_c in the ninth column) for an estimated projection on the line of sight. Each galaxy was observed by the author on photographs, the position of the supernova located and the correction made on the assumption that the supernova lay in the principal plane of the galaxy as estimated from the apparent major and minor axes. The mean ratio of r/r_c for a random distribution of all supernovae directions should be $\pi/4 = 0.79$. The mean ratio from table 1 is 0.82.

TABLE 1

DISTANCES OF SUPERNOVAE FROM NUCLEI

DATE	N. G. C.	TYPE	m_{pg}	$m-M$	$\Delta\alpha \cos\delta$	$\Delta\delta$	r	r_c	REF.
1885	224	S_b	4.5	22.2	− 15″	− 4″	21	34	4
1937	1003	S_c	13.1	26.8	+ 48	− 1	530	740	
1901	2535	SB_c	13.7	28.2	+ 19	+ 7	440	440	5
1920	2608	SB_c	13.6	28.1	− 19	+ 5	400	480	6
1912	2841	S_b	10.6	25.1	− 50	+ 20	270	410	7
1937	4157	S_c	12.0	26.5	+ 42	+ 42	580	930	8
1936	4273	S_c	12.4	26.7	0	+ 29	310	400	9
1926	4303	SB_c	10.4	26.7	− 11	+ 69	740	740	10
1901	4321	S_c	10.5	26.7	−110	+ 4	1170	1170	11
1914	4321	S_c	10.5	26.7	+ 24	−111	1200	1200	11
1895	4424	$S_b$pec	12.5	26.7	+ 75	− 11	810	970	12
1919	4486	E_o	10.1	26.7	− 15	+100	1070	1070	13
1915	4527	S_c	11.3	26.7	+ 44	+ 8	470	620	11
1939	4636	E	10.8	26.7	− 26	+ 20	350	450	
1907	4674	S_b	14.5	29.0	− 10	+ 11	460	680	
1937	I4182	S_c	13.5	24.8	+ 30	+ 40	220	220	
1923	5236	S_c	8.8	24.8	+109	+ 58	550	600	14
1895	5253	Irr.	11.0	25.5	+ 16	+ 23	170	260	15
1934	I4719	S_b	13.9	28.4	+ 6	− 13	330	660	
1917	6946	S_c	11.1	25.3	− 30	−105	610	610	16

Limits in Distance (parsecs)	0–300	301–600	601–900	901–1200
Numbers of Supernovae	3	6	6	5

The angular distances (nova–galaxy nucleus), given in columns six and seven, were obtained from the sources indicated by the references in column ten or were measured by the author from Harvard plates. The distance moduli ($m-M$), apparent magnitudes (m_{pg}) and types for the galaxies were, when available, adopted from Baade's[17] tabulation. In other cases an absolute magnitude of −14.5 was assumed[18] and Miss Sawyer's[19] values of apparent magnitude were used. The year in which the supernova attained maximum light is given in the first column. A questionable supernova which has been omitted from table 1 is the one discovered by Wolf[20] near Messier 101. Its absolute magnitude did not certainly exceed −10 and the light curve was peculiarly flat. Miss Sawyer omitted it from her list. The computed value of r_c is 2060.

The numbers of supernovae for equal steps in nuclear distance are shown at the bottom of table 1. It can be seen that the frequency is fairly uniform with distance, indicating approximately a $1/r$ law of frequency against area in the principal plane of the average galaxy. The surface luminosity is distributed in a similar fashion. It is of importance to notice that few supernovae occur outside the "main bodies" of the galaxies as measured by Hubble.[21] The Crab Nebula appears to have been produced by a supernova[22] and is an exception in regard to position, as would be Wolf's supernova in Messier 101, if real.

A study of the literature and photographs shows that ten of the twenty supernovae listed above were apparently located on the main axis, a conspicuous arm or a condensation of the galaxy. Eight were in areas of intermediate brightness or could not be well studied, and only two were in apparently dark areas. Zwicky[8] states that for N. G. C. 4157 the supernova occurred in an obscured area. Supernova 4321 (1914) occurred outside the brighter regions but was observed on only one plate. As a working hypothesis it seems likely that the supernovae are distributed in an external galaxy as is the luminosity, with perhaps some tendency to avoid the nucleus. Hubble[23] came to this conclusion for the ordinary novae in Messier 31. The quantitative distribution of supernovae in linear distance from the nuclei is remarkably similar to that for the ordinary novae as observed by Hubble.

2. *Theory of Collisions.*—The frequency of stellar collisions may be calculated in the same manner as the frequency of molecular collisions in a gas, except that the effective target area for stellar collisions depends upon the relative velocity of the stars at infinity, as Schwarzschild,[24] Jeans[2] and others have mentioned. For two stars of equal mass, m_0, with relative velocity, v_∞, the radius, σ, of the effective target area (corresponding to the diameter of a molecule in the gas theory) to allow a periastron distance of q_0 between centers is given by

$$\sigma^2 = \frac{4Gm_0q_0}{v_\infty^{\,2}} + q_0^2 \qquad (1)$$

where G is the constant of gravitation and c. g. s. units are employed. For dwarf stars the q_0^2 term is negligible for actual collisions and will be omitted hereafter.

If we assume a Maxwellian distribution of stellar velocities and integrate over all relative velocities, the classical expression for the number of collisions is changed to

$$\frac{\text{Number of Collisions}}{\text{cm.}^3\ \text{sec.}} = 4\sqrt{2}\ Gm_0q_0\ N_0^2/v_0 \qquad (2)$$

where N_0 is the number of stars per cm.^{3} and v_0 is the arithmetic mean velocity.

If the mass of the sun is adopted as unity, N = number of stars per cubic parsec, v = arithmetic mean velocity in km./sec. and q is taken in units of the *radius* of the sun, the expression becomes

$$\frac{\text{Number Collisions}}{(\text{parsec})^3\ \text{year}} = \frac{N^2mq}{v}\ [-15.251], \qquad (3)$$

where brackets indicate a logarithm to the base 10. If a galaxy contains M solar masses uniformly distributed over a volume of V cps., $N = M/mV$, and we find

$$\frac{\text{Number Collisions}}{\text{Galaxy year}} = \frac{M^2q}{mvV}\ [-15.251]. \qquad (4)$$

3. *Collisional Frequency.*—In the application of equation (4) the most uncertain quantity is probably the mass of the main body of a galaxy. We shall adopt values for the other quantities from observation, and calculate collisional frequencies for various estimates of the mass. The average volume may be taken as that of a disc with radius 1000 parsecs and thickness one-third the radius. $V = [+9.02]$ (parsecs).^{3}

The average star is probably of low luminosity and small mass, in accordance with the low mass-luminosity relation for external galaxies and particularly in view of the prevalence of faint stars in our local system. We adopt an absolute bolometric magnitude for the average star of +10 to +11, in rough agreement with Luyten's unpublished results. According to Kuiper[25] the corresponding mass may be taken as $^1/_{10}$ the solar mass and the radius $^1/_3$ the solar radius.

The average stellar velocity should refer to the center of gravity of each local region of the galaxy. According to the *virial* theorem, the velocity should increase with the space density and with the volume assumed to represent local conditions. We adopt v = 100 km./sec. as a representative value.

With these adopted values of V, m, q and v, the number of stellar collisions (limb to center) per galaxy per year is calculated in table 2 for three assumed masses of the main body of an average galaxy. A mass of 5×10^9 suns is considered a minimum value, while 5×10^{10} suns represents perhaps the best present-day estimate.[21,26] A mass of 2×10^{11} suns appears to be an overestimate for the main body of a galaxy, though possibly a fair approximation for the entire system.[27]

For purposes of comparison, the relative frequencies of calculated collisions to observed supernovae are given in the last column of table 2. Zwicky's[28] determination that, on the average, one supernova occurs in a galaxy in six hundred years is adopted.

TABLE 2

COLLISIONAL FREQUENCIES*

TOTAL MASS (SUNS/GALAXY)	DENSITY (SUNS/CU. PARSEC)	COLLISIONS (GALAXY/YEAR)	COLLISIONS / SUPERNOVAE
5×10^9	5	0.0000005	0.0003
5×10^{10}	50	0.00005	0.03
2×10^{11}	190	0.0007	0.4

* For stars like the sun ($m = q = 1$), multiply frequencies by 0.3.

It can be seen from table 2 that under the most extreme conditions the frequency of collisions is comparable with the number of supernovae. The agreement is reduced by a factor of three if the average star is taken to be of the same mass and radius as the sun.

The slight tendency for the supernovae to avoid the nuclei of galaxies, where one might expect the greatest number of collisions, may be explained on the basis of absorbing matter and observational selection. One must note too that the collisional frequency varies inversely as the mean velocity and that the velocity will certainly increase toward the nuclei, thus tending to counteract partially the effect of high central densities.

4. *Energy Considerations.*—The total energy lost by a supernova is somewhat uncertain. If the energy distribution approximates that of the sun, the loss by radiation varies from about 1×10^{47} to 4×10^{48} ergs for the various supernovae.[29] A correction of two to allow for an A-type distribution would probably be sufficient, if the supernovae spectra are similar to novae spectra except for the line widths; otherwise, the factor would probably be larger.[30] In addition, there is an unknown amount of energy lost by the ejection of material at high velocities. It seems probable, at present, that a correction factor of 5 to 10 should allow for both ejection and radiation. In a nova the energy of ejection is smaller than the energy of radiation. We shall assume that the total energy to be accounted for may lie between 10^{48} and 4×10^{49} ergs for the various supernovae.

Two stars similar to the sun in mass and radius would possess 4×10^{48} ergs of kinetic energy at the instant of an edge-to-center encounter. Although this amount of energy is in excellent agreement with that probably released by a supernova, it seems unlikely that a large fraction of the kinetic energy can be converted into radiation. A discussion similar to that by Jeffreys[31] shows that the conservation of angular momentum will force the stars to pass by each other with a small energy loss. It is possible, however, that under the conditions assumed above, five per cent of the kinetic energy may be converted. For stars of $^1/_{10}$ the sun's mass and $^1/_3$ its radius, the energies calculated above are reduced by a factor of 30.

It should be noted that the kinetic energy at the time of collision for stars of equal mass varies *inversely* as the distance of their centers, and that the probability of collision varies *directly* as the distance. In addition, the percentage of the kinetic energy that may be converted into radiation should *increase* with decreasing periastron distance both because of the decreasing amount of angular momentum and because the stars are highly concentrated toward their centers. Thus there will be frequent cases in which the energy release exceeds by a considerable amount the values calculated above.

The effect of the high central concentration of stars is very important. For values of periastron distance above a certain critical value (perhaps 0.6 to 1.0 radius for the Emden polytrope of index 3), the quantity of matter involved in the collision decreases rapidly, as does the amount with negative angular momentum about the center of gravity. Thus the total energy that can be converted into radiation and therefore the total visible radiation of the outburst quickly become negligible with increasing periastron distance. For example, suppose the critical distance were $q = 1.0$ for solar masses and the corresponding radiant energy, 2×10^{47} ergs. Then one should expect an equal number of supernovae with energies above and below this value. The maximum possible energy for solar masses is possibly of the order of 2×10^{49} ergs. Under these assumptions one-half of the supernovae would occur within a range of five magnitudes, the other one-half being fainter over an infinite range. With a mixture of stars of various masses the critical range would be increased but the general effect would be similar to that observed, a concentration near the magnitude of maximum frequency.[17,19]

Discussion.—It is not the purpose of the present paper to compare the various possible hypotheses for the origin of supernovae but to show that the collision hypothesis deserves consideration. There are several phases of the hypothesis that must be critically analyzed before a judgment of its merits can be made. In particular, there is the problem of whether an actual collision would produce the observed phenomenon. In the last section it was assumed that much of the energy from an inelastic collision would be released in the form of radiation. This assumption is open to question until the detailed processes involved are carefully studied. In any case, the equilibrium of the stars must be seriously disturbed by a collision, and it is possible that considerable energy may be released as new states of equilibrium are attained. Eddington,[32] for example, has shown that a star has a store of energy comparable to the amounts assumed for supernovae, while Milne[33] has suggested that novae result from the collapse of stellar cores and Baade and Zwicky[34] that supernovae result in neutron cores. Regardless of the exact process by which the energy is released it is important to note that *the energy will always be associated with matter*, and that the matter will act, by its opacity and expansion, as a blanket to excessively high temperature radiation until some sort of equilibrium is reëstablished.

Another critical point concerns the total energy actually released by a supernova. This quantity is chiefly a matter of opinion until the fundamental characteristics of the spectra are ascertained. The problem is complicated by the ejection of gases at high velocities in the supernova phenomenon.

The problem of the frequency of collisions to be expected in an external galaxy is far from an exact solution as yet. Not only is the mean density of matter uncertain, but the distribution function of stellar masses is practically unknown. In addition, a very careful study of the velocity distribution must be made when the mass functions and densities are better determined.

In spite of these uncertainties, the collision-hypothesis shows promise of providing a logical explanation for the very remarkable phenomenon of the supernovae.

[1] Luyten, *H. A.*, **85,** 73 (1923).
[2] Jeans, *Astronomy and Cosmogony*, p. 319 (1929).
[3] For discussion see *Handbuch der Astrophysik*, Band VI.
[4] Hartwig, *A. N.*, **113,** 21 (1886).
[5] K. Reinmuth, *A. N.*, **221,** 47 (1923).
[6] K. Reinmuth, *A. N.*, **211,** 191 (1920).
[7] Pease, *P. A. S. P.*, **29,** 213 (1917).
[8] Zwicky, *P. A. S. P.*, **49,** 204 (1937) (Position = 1′ NE of nucleus).
[9] Hubble and Moore, *P. A. S. P.*, **48,** 108 (1936).
[10] Shane, *P. A. S. P.*, **38,** 182 (1926).
[11] H. D. Curtis, *P. A. S. P.*, **29,** 180 (1917).
[12] Wolf, *A. N.*, **226,** 75 (1925).
[13] Balansowsky, *A. N.*, **215,** 215 (1922).
[14] Lampland, *P. A. S. P.*, **35,** 166 (1923).
[15] E. C. Pickering, *A. N.*, **139,** 249 (1895).
[16] Ritchey, *A. N.*, **205,** 79 (1917).
[17] Baade, *Ap. J.*, **88,** 285 (1938).
[18] Shapley, these PROCEEDINGS, **19,** 591 (1933).
[19] Miss Sawyer, *J. R. A. S. Can.*, **32,** 69 (1938).
[20] Wolf, *A. N.*, **180,** 245 (1909).
[21] Hubble, *Realm of the Nebulae*, p. 178 (1936).
[22] Mayall, *P. A. S. P.*, **49,** 101 (1937).
[23] Hubble, *Ap. J.*, **69,** 103 (1929).
[24] Schwarzschild, *Seeliger Festschrift*, p. 94 (1924).
[25] Kuiper, *Ap. J.*, **88,** 472 (1938).
[26] Zwicky, *Ap. J.*, **86,** 217 (1937).
[27] S. Smith, *Ap. J.*, **83,** 23 (1936).
[28] Zwicky, *Ap. J.*, **88,** 529 (1938).

[29] Miss Hoffleit, *H. B.* (in press).
[30] Mrs. Payne-Gaposchkin, these PROCEEDINGS, **22,** 332 (1936); Zwicky, *Ibid.*, **22,** 557 (1936).
[31] Jeffreys, *M. N.*, **89,** 731 (1929).
[32] Eddington, *The Internal Constitution of the Stars*, p. 143 (1926).
[33] Milne, *M. N.*, **91,** 4 (1930).
[34] Baade and Zwicky, these PROCEEDINGS, **20,** 259 (1934).

OBSERVATIONS ON CHROMOSOME ELIMINATION IN THE GERM CELLS OF SCIARA OCELLARIS[1]

BY R. O. BERRY

DEPARTMENT OF ZOÖLOGY, JOHNS HOPKINS UNIVERSITY

Communicated February 15, 1939

One of the interesting problems that have arisen in the course of the work with Sciara concerns the time and manner of chromosome elimination from the germ line of this organism. Since the sperm regularly transmits an extra sex chromosome to the fertilized egg (Metz, Moses and Hoppe, 1926),[2] it necessarily follows that a subsequent elimination process must occur in order to maintain a constant chromosome number in the germ line (for general review see Metz, 1938).[3] The sperm contributes five chromosomes, one more than the haploid number, while the egg has the normal haploid number of four. Thus in the fertilized egg there are nine chromosomes. However, observations on the gonads of the early larval stage show that there are only eight chromosomes present. Therefore, one chromosome must have been eliminated at some early stage of development. It is the purpose of this paper to give some of the details of the process of elimination as it occurs in the germ cells.

DuBois (1932, 1933)[4] observed chromosome elimination from the somatic cells of *Sciara coprophila* during the early cleavage stages. In this species the "limited" chromosomes were eliminated at the fifth cleavage, and one ordinary chromosome in the female and two ordinary chromosomes in the male were eliminated at the seventh or eighth cleavage of the cells of the somatic line. In each case the eliminated chromosomes failed to complete the mitotic process and remained at the equatorial plate, thereby being excluded from the daughter nuclei. DuBois also found that the germ cells had migrated into the poleplasm previous to the time of chromosome elimination in the somatic cells, but her observations did not reveal any elimination from the cells of the germ line at that time.

In the present study observations on the chromosomes of the germ cells of *Sciara ocellaris* Comst., have been made from the time of their differentia-