THE ASTRONOMICAL JOURNAL VOLUME 90, NUMBER 11 NOVEMBER 1985

A COMPARATIVE STUDY OF SUPERNOVA LIGHT CURVES

Jesse B. Doggett
Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma 73019
and
Department of Astrophysical, Planetary, and Atmospheric Sciences, University of Colorado, Boulder, Colorado 80309

David Branch
Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma 73019

Received 13 June 1985; revised 16 July 1985

ABSTRACT

Mean light curves of Type I, II-P ("plateau"), and II-L ("linear") supernovae are plotted on a common scale and directly compared. The Type II-P light curve has a distinctive shape, but the shape of Type II-L bears a resemblance to that of Type I in both the *B* and *V* bands. The similarity raises the question of whether the underlying physics of Type II-L explosions is more like that of Type I than like that of Type II-P, contrary to the usual assumption. It is shown that for Tycho's and Kepler's supernovae, light-curve shape cannot distinguish between a Type I and Type II-L classification. The light curves of the principal examples of Zwicky's Type III, IV, and V supernovae are compared directly to the mean light curves of the main types. We suggest that these supernovae be referred to as II-pec, for "Type II peculiar."

I. INTRODUCTION

Ordinarily, supernovae are designated as Type I or Type II according to whether their optical spectra do (Type II) or do not (Type I) contain the hydrogen Balmer lines. Occasionally, if a spectrum is not available, a type is assigned on the basis of the shape of the light curve. Light curves of many individual supernovae, as well as mean light curves for Types I and II, have been published but direct comparisons of the light curves of different types of supernovae, plotted on the same scale, have seldom, if ever, appeared in the literature. The purpose of this paper is to provide such a direct comparison, and to discuss some of its implications. We are concerned here only with the *shapes* of the light curves; the absolute brightness probably never should be used for classification purposes.

II. TYPES I AND II

a) Comparison of Mean Light Curves

A composite light curve for Type I, based entirely on data for 38 SNe I given by Barbon *et al.* (1973a), is shown in Fig. 1. The data consist of both photographic and photoelectric blue magnitudes; in this paper, no distinction between the two is necessary, and the light curve will be referred to as "blue." In spite of the good photometric homogeneity of SNe I, some attempts have been made to subclassify them, based on the rates of fading of their individual light curves (Barbon *et al.* 1973a; Rust 1974; de Vaucouleurs and Pence 1976; Pskovskii 1977; Branch 1982). The physical reality of the light-curve subdivisions still has not been established beyond doubt, so for present purposes we treat SNe I as a single class and ignore the few SNe I that appear to have had pecu-

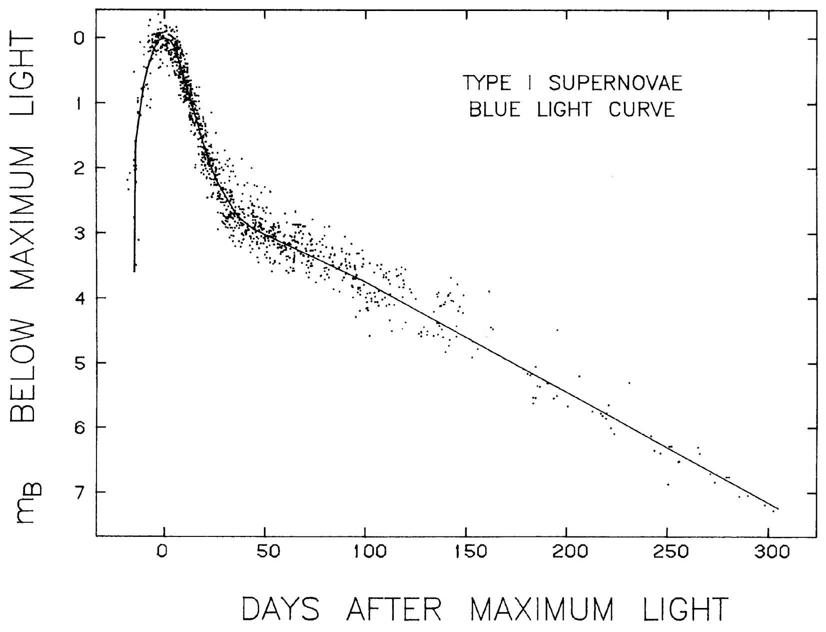


FIG. 1. Composite blue light curve for Type I supernovae, after Barbon, Ciatti, and Rosino (1973a).

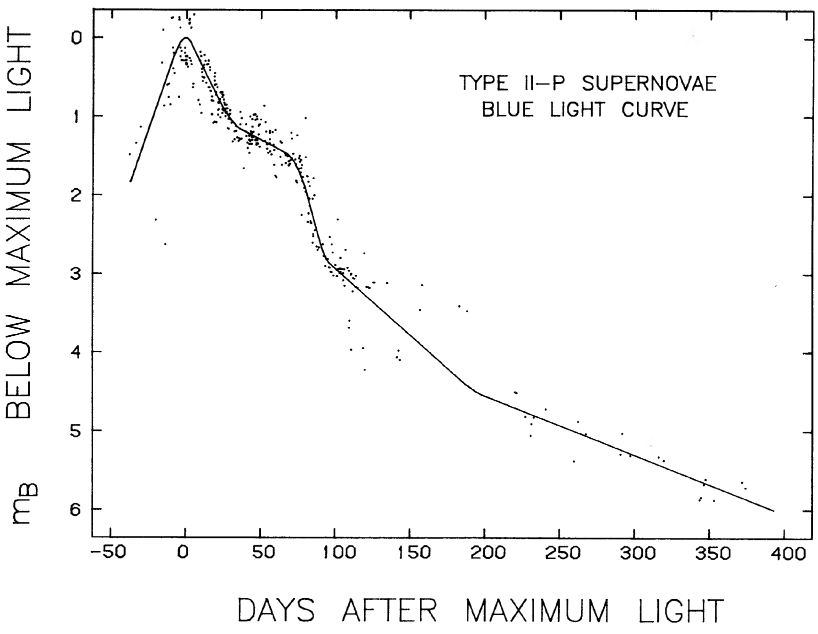


FIG. 2. Composite blue light curve for Type II-P supernovae, after Barbon, Ciatti, and Rosino (1979).

liar light curves. The solid line drawn (by eye) in Fig. 1 will be referred to as the mean light curve. Barbon *et al.* (1973a) discussed the characteristics of the Type I light curve in detail; the mean curve in Fig. 1 has similar properties. Beginning at 100 days after maximum light, our curve declines at a constant rate of 0.017 mag per day. A more detailed study of the late-time light curve has been made by Barbon *et al.* (1984). Their best determination for the slope of the light curve "tail" is 0.015 16 ± − 0.0024 mag day^{-1}, based on data between 200 and 400 days.

Barbon *et al.* (1979) divided the light curves of Type II supernovae into two fairly homogeneous subclasses, called "plateau" (SNe II-P) and "linear" (SNe II-L). Pskovskii (1978a) has proposed a finer subclassification of SNe II, but again the physical reality remains open to question. Here we adopt the plateau and linear scheme. A composite blue light curve based on data for 15 SNe II-P given by Barbon *et al.* (1979) is shown in Fig. 2. Figure 3, for SNe II-L, is based on the data given by Barbon *et al.* (1979) for six events, but supplemented by data for two recent, well-observed SNe II-L, 1979c in M100 and 1980k in NGC 6946. Mean light curves are drawn in Figs. 2 and 3, but note that at late times the data are sparse and somewhat scattered. Barbon *et al.* (1984) found the mean late-time decay rate for SNe II as a class to be 0.008 10 ± − 0.000 21 mag day^{-1}, significantly slower than SNe I. Our mean curves fall at rates of 0.0075

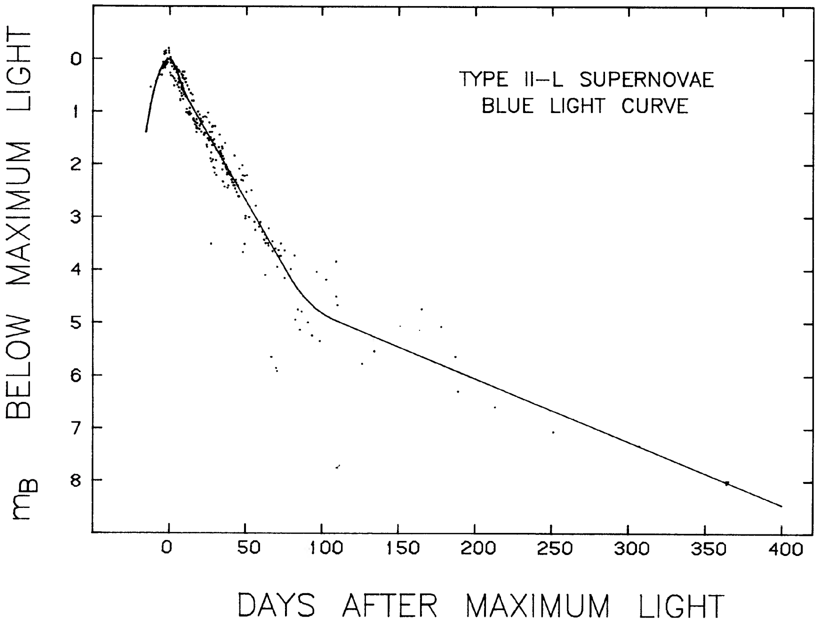


FIG. 3. Composite blue light curve for Type II-L supernovae, (Balinskaya *et al.* 1980; Barbon, Ciatti, and Rossino 1979, 1982a; Ortolani and Rafanelli 1982; Buta 1982; de Vaucouleurs *et al.* 1981).

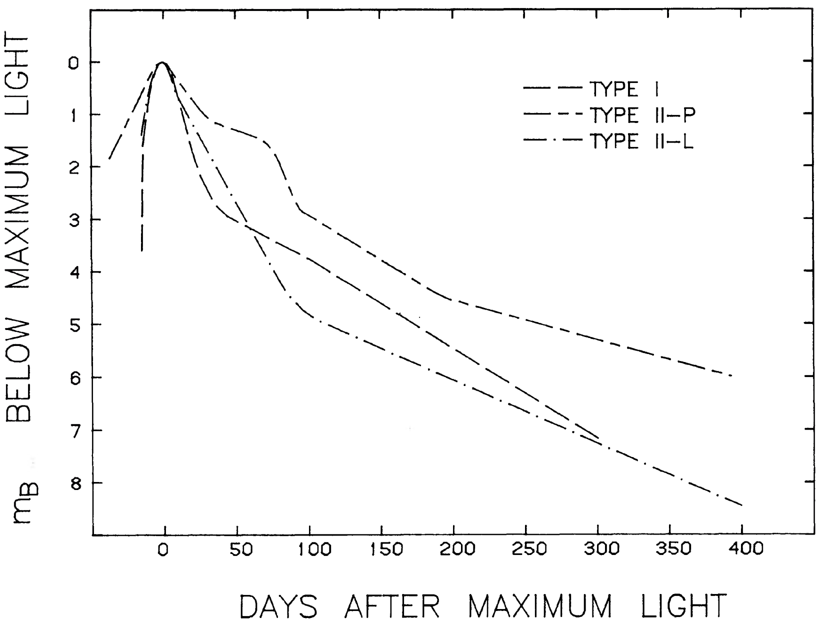


FIG. 4. Comparison of the mean blue light curves for Type I, II-P and II-L supernovae.

(SNe II-P) and 0.012 mag day^{-1} (SNe II-L), but more data are needed to determine whether this difference is real, and to establish the extent to which real differences, rather than observational error, contribute to the scatter.

The shapes of the mean curves for SNe I, II-P, and II-L are compared directly in Fig. 4. For SNe II-P, the phase of nearly constant brightness prior to 80 days constitutes the plateau. This phase is so distinctive that it may be safe to classify a supernova as II-P on light-curve shape alone.

The most interesting aspect of Fig. 4 is the similarity of the SN I and II-L curves. Considering that individual supernovae may show some departures from the mean curves, it may be dangerous to distinguish between SNe I and II-P on the basis of light-curve shape alone. A classification based on a *partial* light curve (the usual situation, for supernovae not observed spectroscopically) certainly could be misleading.

The three mean curves of Fig. 4 can be generated using the data listed in Table I.

b) The Progenitors of SNe II-L?

The similarity of the mean light curves of Types I and II-L raises a question about the origin of the latter. Because Type II supernovae, both II-P and II-L, appear almost invariably in spiral arms, their progenitors must be relatively massive stars. Theoretically, stars initially more massive than 8 $M_\odot$ safely pass through the ignition of nondegenerate carbon and go on to develop heavy-element cores which collapse. The collapse is believed to result in neutron-star formation and shock-wave ejection of the stellar envelope. Diffusive release of the shock energy from the massive expanding envelope accounts for the SNe II-P light curve (Weaver and Woosley 1980; Schrumann, Arnett, and Falk 1979; Chevalier 1976). The duration of the plateau is determined primarily by the mass of the envelope (Litvinova and Nadyozhin 1983). The explosions of SNe II-L may be similar, the primary difference being that their progenitors lose most, but not all, of their hydrogen envelopes before the explosion takes place (Chevalier 1984), and therefore show a shorter or tent plateau. If so, we might expect a larger sample of accurate SNe II light curves to show a continuous range of light-curve shapes rather than two distinct shapes.

Alternatively, the possibility that SNe II-L may be fundamentally related to SNe I should be considered. Ordinary SNe I appear in all kinds of galaxies, and when in spirals they show no preference for the arms (Maza and van den Bergh 1980). The leading model for ordinary SNe I is a carbon-oxygen white dwarf, which is provoked to explode by the

TABLE I. Mean blue light curves.

Type I		Type II-P		Type II-L	
Days	Mag.	Days	Mag.	Days	Mag.
– 15	3.60	– 37	1.83	– 15	1.38
– 14	1.62	– 8	0.22	– 12	0.88
– 10	0.71	– 4	0.05	– 10	0.61
– 8	0.45	– 2	0.01	– 8	0.39
– 5	0.16	– 1	0.00	– 6	0.22
– 3	0.04	0	0.00	– 4	0.10
– 2	0.02	1	0.01	– 2	0.02
0	0.00	2	0.03	0	0.00
2	0.02	3	0.06	1	0.01
3	0.04	4	0.10	2	0.05
4	0.08	25	0.90	4	0.17
6	0.19	29	1.02	10	0.63
7	0.31	34	1.13	11	0.70
22	1.89	36	1.16	12	0.76
26	2.20	40	1.20	14	0.86
35	2.68	68	1.48	80	4.18
37	2.76	72	1.57	84	4.36
44	2.94	76	1.71	88	4.51
100	3.76	80	1.91	96	4.74
305	7.25	81	1.98	102	4.86
		91	2.66	107	4.94
		92	2.72	400	8.46
		94	2.81		
		96	2.86		
		187	4.40		
		194	4.50		
		198	4.54		
		393	6.00		

accretion of matter from a binary companion. A substantial fraction of the white dwarf is burned to the isotope Ni^{56}, whose beta decay through unstable Co^{56} to stable Fe^{56} accounts for the shape of the SN I light curve (Nomoto, Theilemann, and Yokoi 1984; Woosley, Axelrod, and Weaver 1984; Arnett 1982; Chevalier 1981; Sutherland and Wheeler 1984). Unlike SNe I, SNe II-L tend to appear in spiral arms, so their progenitor populations must differ. One possibility is that the progenitors of SNe II-L have initial masses somewhat less than $8\,M_\odot$ and lose most but not all of their hydrogen envelopes before igniting degenerate carbon cores. The physics of the explosion would be much like that of SNe I, but the optical spectrum would reflect the hydrogen-rich envelope, and be Type II. Thus, SNe II-L would correspond to the "Type $1\frac{1}{2}$" supernovae of Iben and Renzini (1983). Detailed observational and theoretical studies are needed to test this possibility.

c) Tycho's and Kepler's Supernovae

The historical supernovae in our galaxy cannot be classified by means of spectra. There has, however, been general agreement that the visual light curves of Tycho's supernova of 1572 and Kepler's of 1604, constructed from contemporary descriptions, are consistent with the light curve of SNe I (Baade 1943, 1945; van den Bergh 1970; Clark and Stephenson 1977; Pskovskii 1978b). Are the Tycho and Kepler light curves also consistent with SNe II-L? To address this question, we have constructed mean *visual* light curves based on 3 SNe I, 2 II-P, and 5 II-L (Figs. 5–7). (Far fewer supernovae have been observed in V than in B). In Fig. 8, these mean visual curves are compared with the light curve of Tycho's supernova (Pskovskii 1978b). Note that in the V band the resemblance of the II-L curve to that of SNe I is even stronger than in the B band. The magnitudes of Tycho's supernova may be more uncertain than indicated, but even if the uncertainties are taken at face value, no distinction between Types I and II-L can be made. For Kepler (Fig. 9), the situation is similar. Kepler is consistent with both SN I and II-L, provided that the low points near 30 days are disregarded (otherwise, Kepler's light curve was inconsistent with *all* extragalactic supernovae observed so far).

The peak absolute magnitudes of the Tycho and Kepler supernovae also fail to establish their types. First, the Tycho and Kepler absolute magnitudes are not well known, owing to uncertainties in their peak apparent magnitudes, reddenings, and distances. Second, while SNe II are on the average fainter than SNe I by about one magnitude (Tammann 1982), at least one SNe II-L, SN 1979c (de Vaucouleurs *et al.* 1981), was as luminous as SNe I. Nor can the present physical characteristics of the supernova remnants be used for a classification, in view of the possibility that SNe II-L are fundamentally like SNe I.

One possible reason for preferring a Type I classification for Tycho and Kepler is based on their positions in the Galaxy. SNe II appear preferentially in spiral arms and therefore are confined to the planes of their parent galaxies. SNe I occur throughout the disk, and presumably are less tightly confined to the plane. At a distance of 3–5 kpc, the Kepler remnant is 350–600 pc from the plane of the Galaxy, which would be unexpected for a Type II. Tycho, at a distance of 2.5–4 kpc, is 60–100 pc out of the plane, which is too small to provide a strong argument for a Type I classification.

III. ZWICKY'S TYPES III, IV, AND V

Zwicky's (1965) Type III, IV, and V were each represented by only one fairly well-observed supernova. A few others sometimes have been suggested as possible additional members of these classes, but only on the basis of little data. The principal example of Type III was SN 1961i in NGC 4303. Spectroscopically, it was like Type II (e.g., Oke and Searle 1974), although the Balmer lines were slow to develop and may have been broader than in typical SNe II. The only light curve published for this supernova was a "schematic" one, based on "some very approximate estimates" (Zwicky 1965), presumably photographic. This light curve is compared with the mean curves of the main types of Fig. 10. SN

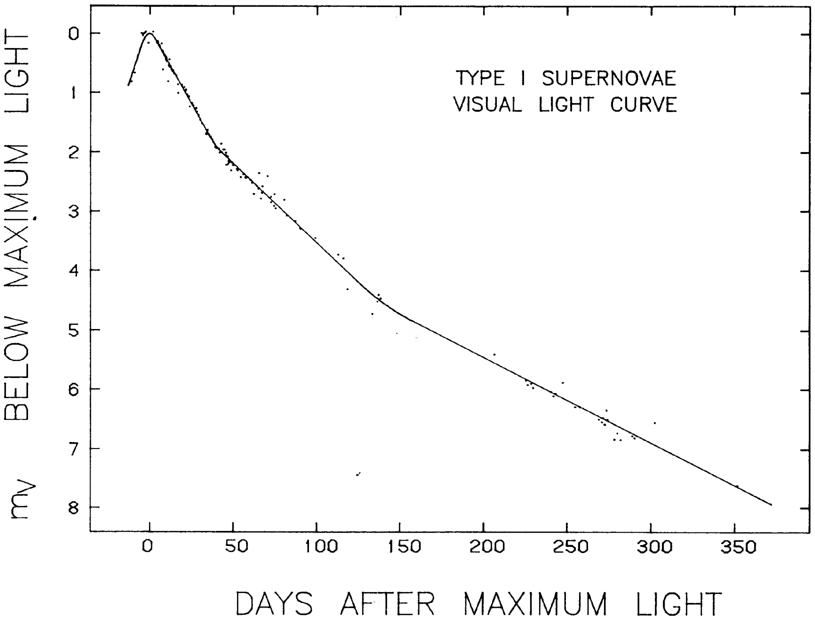


FIG. 5. Composite visual light curve for Type I supernovae (Barbon, Ciatti, and Rosino 1973b; Ardeberg and de Groot 1973, 1974; Lee *et al.* 1972; Van Genderen 1975; Buta and Turner 1983).

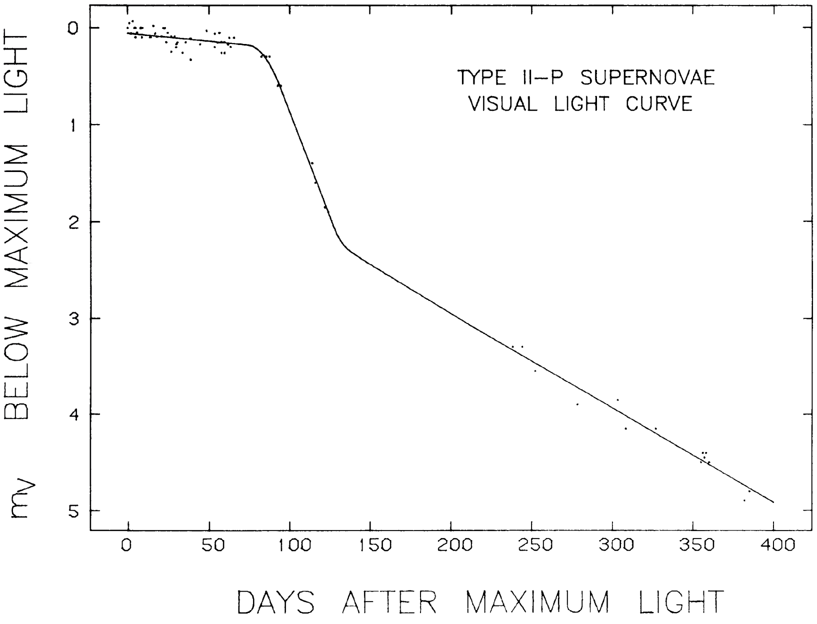


FIG. 6. Composite visual light curve for Type II-P supernovae (Wood and Andrews 1974; Ciatti, Rosino, and Bertola 1971).

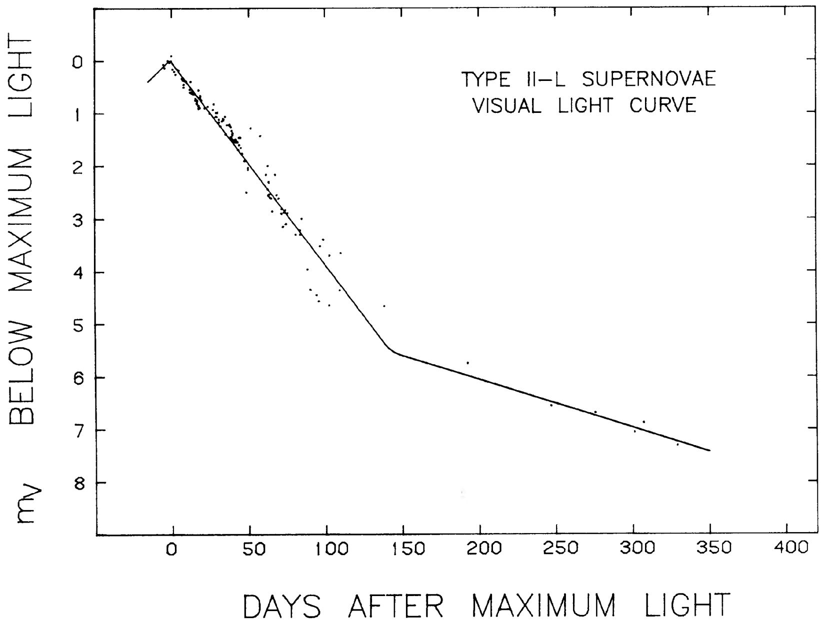


FIG. 7. Composite visual light curve for Type II-L supernovae (Arp 1961; Gates *et al.* 1967; Barbon, Ciatti, and Rosino 1973c; Balinskaya *et al.* 1980; Barbon *et al.* 1982a,b; de Vaucouleurs *et al.* 1981; Buta 1982).

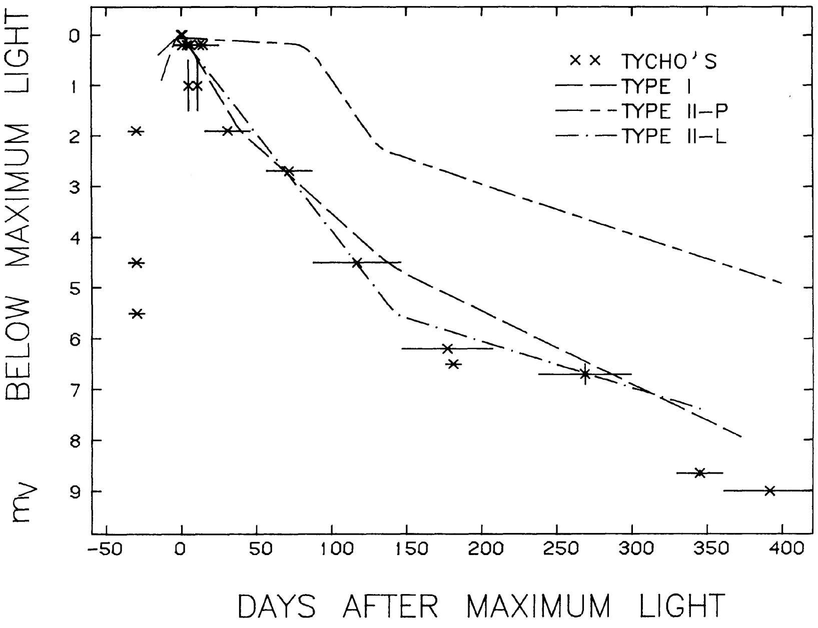


FIG. 8. Comparison of the light curves of Tycho's supernova (Pskovskii 1978b) with the mean visual light curves of Type I, II-P, and II-L supernovae. Horizontal lines through the data points indicate the time interval to which the magnitude estimate applies, and vertical lines refer to an estimated magnitude range.

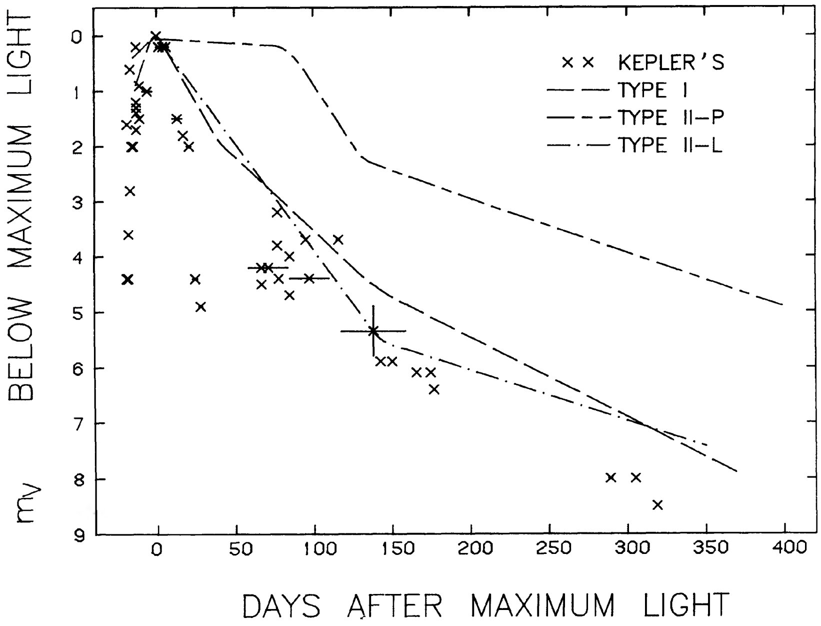


FIG. 9. Like Fig. 8, but for Kepler's supernova.

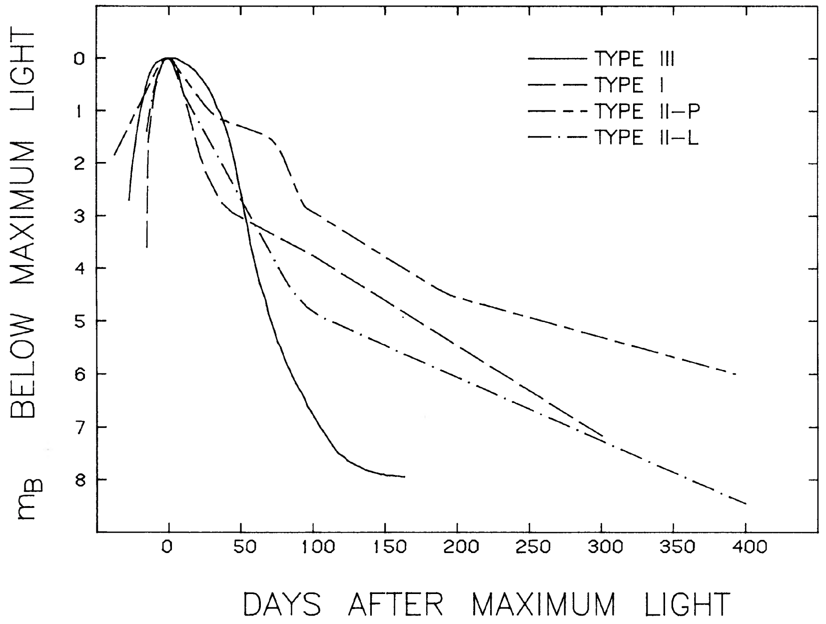


FIG. 10. Comparison of the approximate light curve of Zwicky's Type III supernova, 1961i in NGC 4303, as reported by Zwicky (1965), with the mean blue light curves of Type I, II-P, and II-L supernovae.

1961i apparently had an extended peak, but then decayed quickly beyond 50 days. If the light curve is reasonably accurate, SN 1961i was indeed different from ordinary SNe II.

SN 1961f in NGC 3003 was the principal example of Type IV. Again, the spectrum showed hydrogen lines (Oke and Searle 1974), at least in absorption; the emission components appear to have been weak. The light curve (Fig. 11) was provided to Zwicky (1965) by G. Haro of the Tonantzintla Observatory. This light curve is not very different from the mean curve for SNe II-P. If the last data point is correct, it indicates perhaps a shorter than average plateau for SN 1961f.

Zwicky's Type V, SN 1961v in NGC 1058, also showed hydrogen lines, although they were Doppler broadened by only 2000 km s^{-1} (Branch and Greenstein 1971), compared to 5000–10 000 km s^{-1} in ordinary SNe II. The light curve (Fig. 12) was even more unusual than the spectrum. Zwicky (1964) found from prediscovery plates that the object had been visible as an 18th magnitude star for at least 25 yr before the explosion. The post-peak decline (Fig. 13) was extraordinarily slow; the supernova was seen by Bertola and Arp (1970) 8 yr after maximum light, while no other supernova has been observed optically more than 2 yr after maximum. Primarily on the basis of the pre-explosion luminosity and

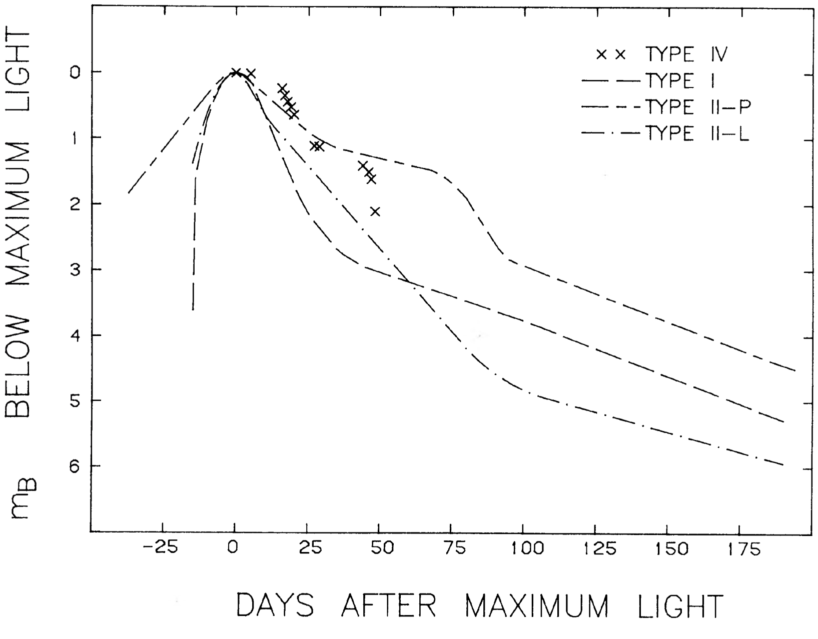


FIG. 11. Like Fig. 10, but for Zwicky's Type IV supernova, 1961f in NGC 3003 (Zwicky 1965).

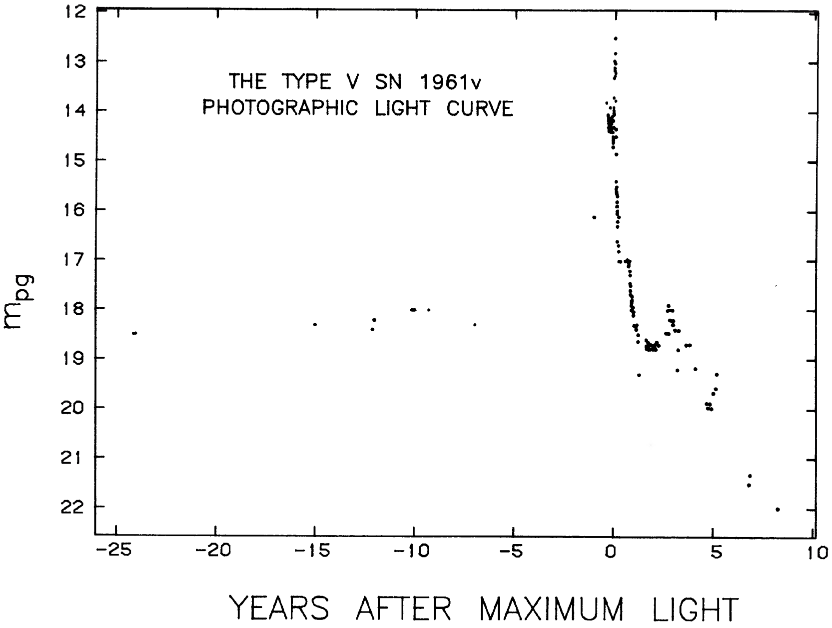


FIG. 12. Blue light curve of Zwicky's Type V supernova, 1961v in NGC 1058 (Zwicky 1964b; Bertola 1963, 1965, 1967; Bertola and Arp 1970).

the slow post-peak decay, Utrobin (1984) has argued that SN 1961v may have ejected 2000 $M_\odot$. The light curve near maximum light is compared to the mean curves of the main types in Fig. 14. Coincidentally (?), the light curve follows that of SNe I for the first 100 days after maximum light.

IV. SUMMARY AND DISCUSSION

The comparison of the mean light curves of the main kinds of supernovae has shown that the SN II-P shape is quite distinct, but the SN II-L shape bears a resemblance to that of SN I. One probably should not attempt to make a distinction between SN I and SN II-L based on light-curve shape alone. It certainly is not possible to use the light curve to make a distinction between Type I and Type II-L for Tycho's and Kepler's supernovae. The similarity also raises the question of whether the underlying physics of SNe II-L explosions might be more closely related to SNe I than to SNe II-P.

The principal examples of Zwicky's Types III, IV, and V supernovae all appeared in 1961, and all showed hydrogen lines. The light curve of Type V was radically different from other supernovae, that of Type III apparently was peculiar, and that of Type IV may have been only mildly unusual. The simple spectroscopic criterion for classification as Type I and Type II, depending on the presence or absence of hydrogen, is a good one. Since peculiar supernovae of both main types have been seen, but no firm understanding of their physical differences has yet been achieved, it seems best to us to use only two types for the time being. To emphasize their

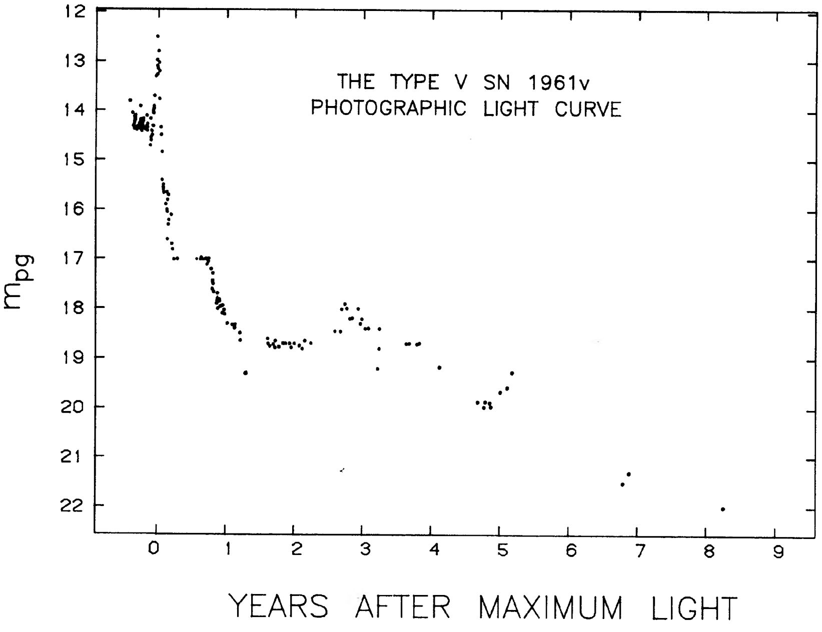


FIG. 13. Like Fig. 12, but restricted to the post-explosion phase.

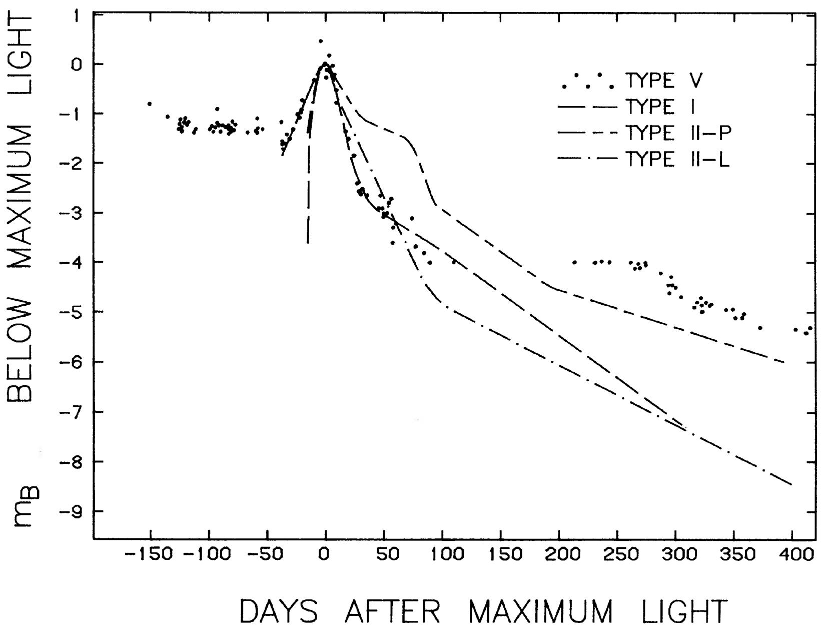


FIG. 14. Comparison of the blue light curve of Zwicky's Type V supernova 1961v in NGC 1058, near maximum light, with the mean blue light curves of Type I, II-P, and II-L supernovae.

spectroscopic relationship to SNe II, we suggest that Zwicky's Types III, IV, and V be referred to as II-pec, for "Type II peculiar."

This work has been supported by NSF Grants Nos. AST 82-18625 to D. B. and AST 82-16491 to M. Shull. We wish to thank R. Fesen for a critical reading of the manuscript.

REFERENCES

Ardeberg, A. L., and de Groot, M. J. (1973). Astron. Astrophys. **28**, 295.

Ardeberg, A. L., and de Groot, M. J. (1974). In *Supernovae and Supernova Remnants*, edited by C. B. Cosmovici (Reidel, Dordrecht), p. 103.

Arnett, W. D. (1982). Astrophys. J. **253**, 785.

Arp, H. (1961). Astrophys. J. **113**, 883.

Baade, W. (1943). Astrophys. J. **97**, 119.

Baade, W. (1945). Astrophys. J. **102**, 309.

Balinskaya, I. S., Bychkov, K. V., and Neizvestny, S. I. (1980). Astron. Astrophys. **85**, L19.

Barbon, R., Cappellaro, E., Ciatti, F., Turatto, M., and Kowal, C. T. (1974). Astron. Astrophys. **135**, 27.

Barbon, R., Ciatti, F., and Rosino, L. (1973a). Astron. Astrophys. **25**, 241.

Barbon, R., Ciatti, F., and Rosino, L. (1973b). Asiago Contrib. No. 248.

Barbon, R., Ciatti, F., and Rosino, L. (1973c). Astron. Astrophys. **29**, 57.

Barbon, R., Ciatti, F., and Rosino, L. (1979). Astron. Astrophys. **72**, 287.

Barbon, R., Ciatti, F., and Rosino, L. (1982a). Astron. Astrophys. **116**, 35.

Barbon, R., Ciatti, F., Rosino, L., Ortolani, S., and Rafanelli, P. (1982b). Astron. Astrophys. **116**, 43.

Bertola, F. (1963). Asiago Contrib. No. 142.

Bertola, F. (1964). Astron. J. **69**, 236.

Bertola, F. (1965). Asiago Contrib. No. 171.

Bertola, F. (1967). Inf. Bull. Var. Stars No. 196.

Bertola, F., and Arp. H. (1970). Publ. Astron. Soc. Pac. **82**, 894.

Branch, D. (1982). Astrophys. J. **258**, 35.

Branch, D., and Greenstein, L. (1971). Astrophys. J. **167**, 89.

Buta, R. (1982). Publ. Astron. Soc. Pac. **94**, 578.

Buta, R., and Turner, A. (1983). Publ. Astron. Soc. Pac. **95**, 72.

Chevalier, R. A. (1976). Astrophys. J. **207**, 872.

Chevalier, R. A. (1981). Astrophys. J. **246**, 267.

Chevalier, R. A. (1984). Ann. N.Y. Acad. Sci. **422**, 215.

Ciatti, F., Rosino, L., and Bertola, F. (1971). Mem. Soc. Astron. Ital. **42**, 163.

Clark, D. H., and Stephenson, F. R. (1977). *The Historical Supernovae* (Pergamon, Oxford).

de Vaucouleurs, G., and Pence, W. D. (1976). Astrophys. J. **209**, 687.

de Vaucouleurs, G., de Vaucouleurs, A., Buta, R., Ables, H. D., and Hewitt, A. V. (1981). Publ. Astron. Soc. Pac. **93**, 36.

Gates, H., Zwicky, F., Bertola, F., Ciatti, F., and Rudnicki, K. (1967). Astron. J. **72**, 912.

Iben, I. I., and Renzini, A. (1983). Annu. Rev. Astron. Astrophys. **21**, 271.

Lee, T. A., Wamsteker, W., Wisniewksi, W. Z., and Wdowaik, T. J. (1972). Astrophys. J. Lett. **177**, L59.

Litvinova, I. Y., and Nadyozhin, D. K. (1983). Astrophys. Space Sci. **89**, 89.

Maza, J., and van den Bergh, S. (1976). Astrophys. J. **204**, 519.

Nomoto, K., Theilemann, F.-K., and Yokoi, K. (1984). Astrophys. J. **286**, 644.

Oke, J. B., and Searle, L. (1974). Annu. Rev. Astron. Astrophys. **12**, 315.

Pskovskii, Yu. P. (1977). Sov. Astron.-AJ **21**, 675.

Pskovskii, Yu. P. (1978a). Sov. Astron.-AJ **22**, 201.

Pskovskii, Yu. P. (1978b). Sov. Astron.-AJ **22**, 420.

Rust, B. W. (1974). Ph.D. thesis, University of Illinois.

Schurmann, S. R., Arnett, W. D., and Falk, S. W. (1979). Astrophys. J. **230**, 11.

Sutherland, P. G., and Wheeler, J. C. (1984). Astrophys. J. **280**, 282.

Tammann, G. A. (1982). In *Supernovae: A Survey of Current Research*, edited by M. J. Rees and R. J. Stoneham (Reidel, Dordrecht), p. 371.

Utrobin, V. P. (1984). Astrophys. Space Sci. **98**, 115.

van den Bergh, S. (1970). Nature **225**, 503.

Van Genderen, A. M. (1975). Astron. Astrophys. **45**, 429.

Weaver, T. A., and Woosley, S. E. (1980). Ann. N. Y. Acad. Sci. **336**, 335.

Wood, R., and Andrews, P. J. (1974). Mon. Not. R. Astron. Soc. **167**, 13.

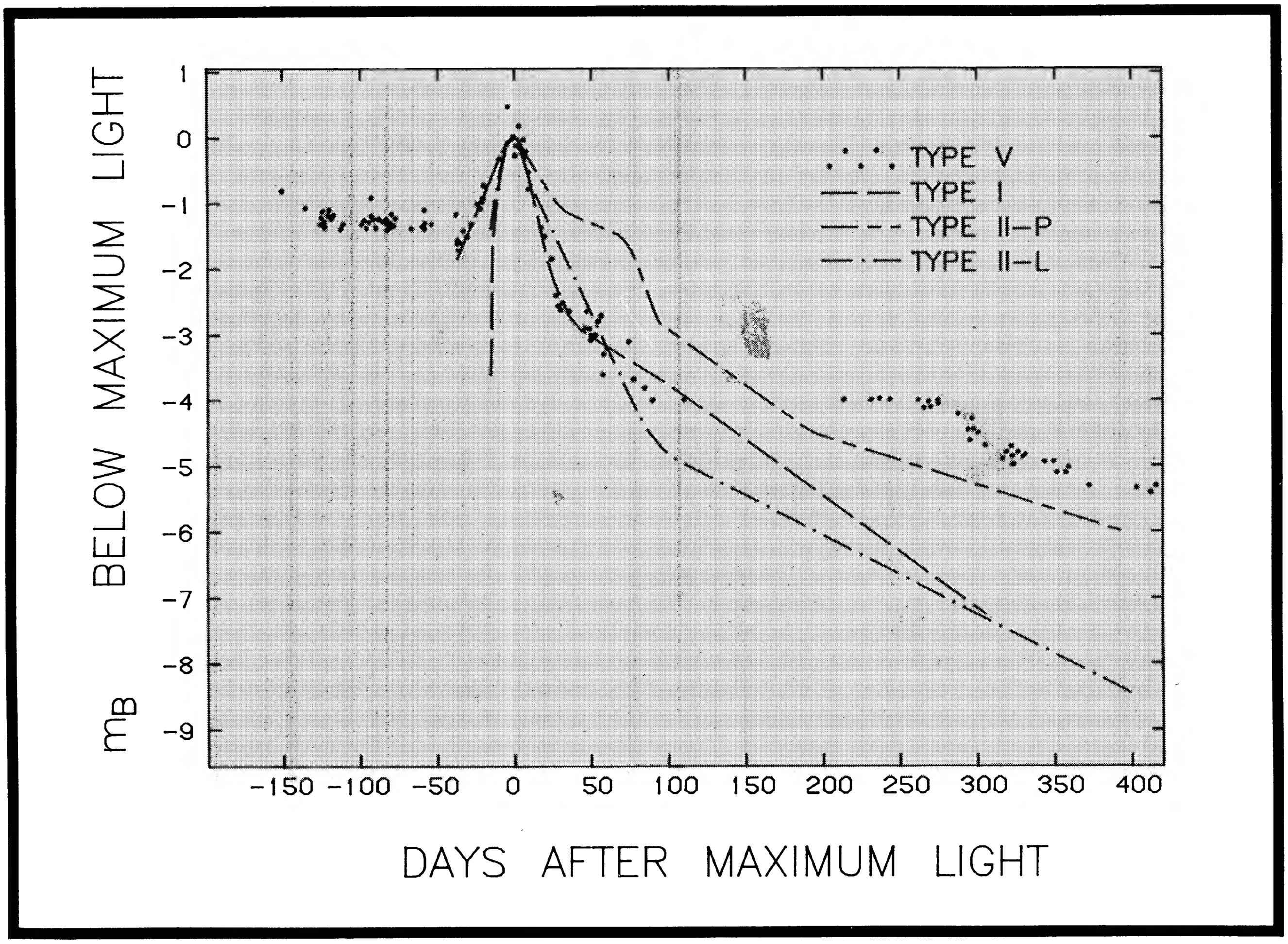
Woosley, S. E., Axelrod, T. S., and Weaver, T. A. (1984). In *Stellar Nucleosynthesis*, edited by C. Chiosi and A. Renzini (Reidel, Dordrecht), p. 263.

1985AJ.....90.2303D

THE ASTRONOMICAL JOURNAL

FOUNDED BY B. A. GOULD
1849

VOLUME 90 **November 1985 ~ No. 1558** *NUMBER 11*



(See Page 2303)

Published for the
AMERICAN ASTRONOMICAL SOCIETY
by the
AMERICAN INSTITUTE OF PHYSICS