FURTHER DATA BEARING ON THE IDENTIFICATION OF THE CRAB NEBULA WITH THE SUPERNOVA OF 1054 A.D.

PART II. THE ASTRONOMICAL ASPECTS

By N. U. Mayall and J. H. Oort

The early attempts to link the rapidly expanding Crab Nebula with the "guest-star" observed in the Far East in 1054 A.D. were concerned, at first, with pointing out that both objects were found in very nearly the same place in the sky,[1] and that the present size and rate of expansion[2] of the nebula indicate that it began to expand at approximately the same time the nova appeared.[3] Later, when order-of-magnitude estimates for the apparent brightness of the 1054 nova[4] and for the distance of the nebula[5] became available, the evidence was discussed by a number of persons[6] with the object of showing that the 1054 guest-star probably was a supernova.

The supernova character of the apparition could not, however, conservatively be regarded as established, for the ancient records hitherto known did not provide sufficiently convincing data relating to the maximum brightness and duration of visibility to make the identification certain. But with the publication of Professor Duyvendak's translations, in particular the new ones wherein the nova is reported to have been seen in daylight and followed for almost two years, it is now possible

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[1] Lundmark, *Pub. A.S.P.*, **33**, 234, 1921.

[2] Duncan, *Mt. W. Comm.*, No. 76; *Proc. Nat. Acad.*, **7**, 179, 1921.

[3] Hubble, *A.S.P. Leaflets*, No. 14, 1928.

[4] Iba, *Pop. Astr.*, **43**, 251, 1934.

[5] Mayall, *Pub. A.S.P.*, **49**, 104, 1937. Lundmark in *Pop. Astr. Tidskr.*, **7**, 18, 1926 (*Upsala Medd.*, No. 12) had earlier used the same method, but different data, to estimate the parallax of the Crab Nebula.

[6] [The Editor] *J. British Astr. Assoc.*, **47**, 274, 1937; Morgenroth, *Die Sterne*, **17**, 255, 1937; Baade, *Ap. J.*, **88**, 303, 1938; *Mt. W. Contr.*, No. 600; Lundmark, *Festskrift tillägnad Östen Bergstrand*, p. 89, 1938; Mayall, *A.S.P. Leaflets*, No. 119, 1939; Zwicky, *Rev. of Mod. Phys.*, **12**, 71, 1940.

to make a strong case for the conclusion that the 1054 temporary star was, in fact, a supernova. In the following paragraphs we shall discuss these new and invaluable data with a view toward demonstrating, in a semi-quantitative way, that the 1054 new star was not only a supernova, but that it probably was one of the brightest supernovae on record.

The distance to the Crab Nebula, as one of the two quantities that determine the maximum absolute magnitude of the 1054 nova, may be estimated by the generally accepted method which assumes equality in the rates of angular and radial expansion of the nebula. By combining the most recent measure of the angular expansion obtained by Duncan,[7] 0".21 per year, with a determination of the radial expansion made by one of the authors,[8] 1300 km/sec, a distance of 1250 parsecs (4100 light-years) is found. The corresponding distance modulus $m-M$ is 10.5, which is obviously independent of galactic absorption. To estimate the uncertainty in the distance from the proper motion and radial velocity measures probably is not worth while, for the greater part of the uncertainty doubtless lies in the basic assumption of equal motion across and in the line of sight, and we are unable to judge how nearly equal are these two components.

The maximum apparent magnitude of the 1054 nova, as the second of the two quantities that determine its maximum absolute magnitude, may be estimated from the Chinese observation that "it was visible by day, like Venus." While from this record we might infer that the nova was apparently as bright as —4, or intrinsically as bright as —14½, we do not consider the result to be altogether satisfactory, for two reasons. First, it is clear that the comparison of the nova with Venus, as made by the Chinese, provides but the crudest estimate. Second, no allowance is made for galactic absorption.

A better way to estimate the maximum apparent magnitude appears to be to use the additional information: "Altogether it was visible for 23 days." If this remark is interpreted to mean that the nova was seen in daylight for 23 days, then the maxi-

[7] *Ap. J.*, **89**, 482, 1939; *Mt. W. Contr.*, No. 609.

[8] Mayall, *Pub. A.S.P.*, **49**, 104, 1937.

mum apparent magnitude, $m_{max.}$, may be found from the simple equation

$m_{max.} = \Delta m + m_l$, in which

Δm = the magnitude difference representing the decline in light from maximum to the limit of daylight visibility;

m_l = the limiting apparent magnitude of an object that can be seen with the unaided eye in daylight.

An approximate value for Δm may be obtained from M. Beyer's[9] visual observations of several modern supernovae near maximum. According to these estimates, the decline in light during the first 23 days past maximum for the three supernovae in the extragalactic systems IC 4182, NGC 1003, and NGC 4636 amounted to —1.3, —1.5, and —1.6 vis. mag., respectively.[10] We therefore shall use the mean in round numbers, —1½ vis. mag., as a reasonable value for Δm.

It is of interest to note that the value of Δm expressed in photographic magnitudes is closer to —2 or —2½, as may be deduced from Baade's comprehensive discussion of photographic observations of a number of modern supernovae.[11] Evidently the decline in brightness of supernovae just past maximum is more rapid in photographic than in visual light; that is to say, the color-index increases at that time. This result is in agreement with the spectral changes observed in two recent supernovae by Minkowski,[12] who found that the visual part of the spectrum strengthens relatively to the photographic region during the first 40 days past maximum. Right at maximum, however, the visual and photographic observations indicate that the color-index is

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[9] *A.N.*, **268**, 350, 1939.

[10] The only other visual light-curve for a supernova known to us is K. Lundmark's reconstruction of the one for S Andromedae (*Kungl. Svenska Vetensk. Handl.*, **60**, No. 8, p. 55, 1920). From his Fig. 8, the decline in light during the first 23 days past maximum is found to be 2.5 vis. mag., or one magnitude more than that indicated by Beyer's estimates. We use the latter mainly because they form a homogeneous series, whereas the data for the light-curve of S Andromedae came from many different sources.

[11] Baade, *Ap. J.*, **88**, 303, 1938; *Mt. W. Contr.*, No. 600.

[12] *Ap. J.*, **89**, 156, 1939; *Mt. W. Contr.*, No. 602.

negligibly small. Thus the maximum absolute visual magnitude of the 1054 nova, derived below, may be directly compared with the mean maximum absolute photographic magnitude of other supernovae.

In order to estimate m_l, we make general reference to the literature of planetary observations, in which there frequently occurs the statement that Venus may be seen in daylight with the unaided eye at nearly all points of its orbit. To mention but one example, Ch. André[13] cites an observation, made by himself and Angot just before the transit of December 8, 1874, in which Venus was seen in full daylight with the naked eye up to 4 days before conjunction, despite unfavorable atmospheric conditions. Since the apparent magnitude of Venus, in this instance, was -3.3, it seems reasonable to infer that an object of $-3\frac{1}{2}$ vis. mag. could readily been seen farther from the sun, especially if the observer knew just where to look. In the case of the Chinese observations, the nova was discovered close to ζ Tauri in the early morning sky, at a time (July 4) when the sun was more than two hours east of the nova. When the latter could no longer be seen in daylight, the sun was nearly four hours east. Under these circumstances, the Chinese probably knew precisely where to look for their guest-star in daytime, and may have been able to follow it in daylight to an apparent magnitude of $-3\frac{1}{2}$, which we shall therefore take as m_l.

With the values of $\Delta m = -1\frac{1}{2}$ mag. and $m_l = -3\frac{1}{2}$ mag., it follows that $m_{\text{max.}} = -5$, a value which we regard as a fairly conservative estimate for the brightness of the 1054 nova seen by the Chinese. Since $m_{\text{max.}}$ is an observed quantity, it may be affected by galactic absorption, and we shall therefore examine this question before deducing the maximum luminosity of the old nova.

The galactic co-ordinates of the Crab Nebula ($l = 152°$, $b = -4°$), the distance of more than a thousand parsecs, the absence of extragalactic nebulae in the surrounding field, and the colors of a number of B stars located in the general vicinity and at nearly the same distance as the nebula, are facts which suggest that the galactic absorption may not be ignored. The

[13] *Les Planètes* (Paris, 1909), p. 11.

colors of the neighboring B stars, as measured by Stebbins, Huffer, and Whitford,[14] indicate, in fact, a total visual absorption of about 1 mag.[15]

With an allowance of 1 mag. for galactic absorption, together with an observed $m_{max.} = -5$, the true maximum apparent magnitude would accordingly be —6, which leads to a maximum absolute magnitude of —16½. Since Baade found from the modern observations of supernovae that the average absolute photographic magnitude at maximum is —14.3, with the most luminous being —16.6, it appears that the 1054 nova may have been one of the brightest supernovae on record.

The case for the supernova character of the phenomenon may be strengthened still further by a consideration of the rate of decline in light from maximum to naked-eye invisibility. For this time interval the Chinese records yield a value close to 650 days. Within that time the nova probably declined from the —5 to the +6 apparent magnitude, or by 11 mag. This magnitude-drop may be compared with that indicated by the light-curve published by Baade and Zwicky[16] for the supernova in IC 4182, which attained the highest known luminosity of —16.6. Although their photographic observations extend only to a point about 280 days past maximum, the gradient (after the "hump" at maximum) is so uniform that the light-curve may reasonably be extrapolated to a point 650 days beyond maximum. By this procedure, we find a magnitude-drop of 11.2 mag., which agrees

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[14] *Ap. J.*, **19**, 20, 1940; *Mt. W. Contr.*, No. 621.

[15] This estimate is obtained as follows: In Table 3 of Stebbins, Huffer, and Whitford's paper there are listed 5 B stars which are within a distance of 5° from the Crab Nebula, and which have corrected distance moduli $m_0 - M \geqslant 9.0$; for these stars the mean $m_0 - M$ is 10.0, and the observed color excess, E_1, averages +0.15 mag. on the color scale employed. In a previous paper (*Ap. J.*, **90**, 209, 1939; *Mt. W. Contr.*, No. 617) the same authors give reasons for taking the total visual absorption as $7E_1$, which, in this case, is 1.0 mag. This figure is unchanged if the area around the nebula is increased to include the B stars within a distance of 10°. In this larger area there are listed 24 B stars with $m_0 - M \geqslant 9.0$; the mean E_1 is again +0.15 mag., and the average $m_0 - M$ is 10.1.

[16] *Ap. J.*, **88**, 416, 1938; *Mt. W. Contr.*, No. 601.

exactly with that inferred from the Chinese records of the 1054 supernova.[17]

The comparison by the Japanese of the nova's brightness with that of Jupiter could indicate that their observation was made on the ascending branch of the light-curve, if Professor Duyvendak has correctly dated their record 16 to 6 days earlier than the first Chinese observation. At the time of the apparition, Jupiter was not far from conjunction[18] with the sun, and its apparent magnitude was close to —1.3. A brightness of this order for the nova, if it occurred about a week before a maximum observed brightness of —5, could be reconciled with the few pre-maximum observations of other supernovae. This view of the Japanese brightness-estimate does not, however, inspire much confidence, because at the time in question Jupiter was an evening object, while the nova was a morning object. Under these circumstances, a simultaneous comparison of the two objects was impossible, and the statement that the nova "was as large as Jupiter" probably is a gross underestimation of the actual apparent brightness of the nova, as Lundmark[19] has already pointed out.

While the case for the supernova character of the 1054 guest-star, and its identification with the Crab Nebula, seems to us to be so strong as to admit of no serious doubts, it may be worth while to note several apparent inconsistencies in the ancient chronicles and in the modern measures of expansion. In the Chinese record translated for the first time by E. Biot, there

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[17] Dr. Baade kindly informs us, in a private communication, that later observations of the supernova in IC 4182 extend the light-curve to 640 days past maximum; during that interval the supernova declined to nearly the 20.0 pg. mag., or 11.4 mag. fainter than at maximum. Furthermore, the light-curves in visual and photographic light run parallel to each other after about 100 days past maximum. The extrapolation above is therefore completely justified.

[18] The approximate positions of the sun, Jupiter, and ζ Tauri on A.D. 1054 July 4 were as follows:

	Sun	Jupiter	ζ Tauri
Right Ascension....	$7^h\ 18^m$	$8^h\ 24^m$	$4^h\ 42^m$
Declination.....	+ 22°	+ 19°	+ 20°

[19] *Festskrift tillägnad Östen Bergstrand,* p. 97, footnote.

is the statement that the nova appeared to the "south-east of T'ien kuan (ζ Tauri)." The Crab Nebula, however, is about 1¼° northwest of ζ Tauri. In order to examine this discrepancy, a search was made of the literature of Chinese uranographies, and the result is that the asterism T'ien kuan cannot be located much more precisely than "near ζ Tauri."[20] The identity in position of the nova and nebula is therefore as close as a comparison of Oriental and Occidental uranographies will allow.

A second, and apparently more serious discrepancy in the Chinese accounts is the observation from Peking that "a guest-star had appeared in the Pleiades" in the interval January 31 to March 1, 1055. Although Professor Duyvendak considers this report to refer to the same object that was discovered July 4, 1054 near ζ Tauri by the star-gazers at K'ai-feng, the large differences in time (7 to 8 months) and in position in the sky (some 30°) contained in the two records make it doubtful, in the absence of further information, that the same object is involved. If, however, the Peking chronicle really does refer to the same guest-star as the K'ai-feng account, the explanation for the difference in position, at least, may come from an Oriental practice of specifying first the general location in the sky, followed by a more exact designation. An example of this practice is the text in the *Mei Getsuki,* wherein the guest-star is said to have appeared in the "orbit," or "location," of Orion, but that it "shone like a comet in *T'ien-kuan* [ζ Tauri]." But until, or unless, the Peking record is amplified in some such manner, it seems best not to regard it as an independent, corroboratory account of the 1054 nova.

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[20] The situation seems best described by John Reeves in an article on Chinese constellations, published in Robert Morrison's *Chinese Dictionary* (1819, Vol. II, Part I, p. 1064), who states in his introduction ". . . . there are still a few stars, chiefly between the horns of Taurus, and others, between [longitudes] 353° and 356°, which admit of doubt." Reeves, nevertheless, connects *T'ien-kuan* with three stars, which he calls ζ 1169, 1217, S°M 1192 of Taurus. We have not been able to identify these stars in any catalogue or on any chart. It is also of interest to note that Gustave Schlegel, in his *Uranographie Chinois* (1875), gives five different groups of stars as *T'ien-kuan,* but finally concludes (p. 373) that it consists of but two stars, ζ Tauri and 126 Flamsteed (BD +16°841).

The modern observations of the angular expansion of the Crab Nebula may, from one point of view, seem to be inconsistent with the identification of the nebula with the 1054 nova. Duncan, from his most recent measures, found the date of outburst for the nebula to be 1172 A.D. A slightly different treatment of the same measures, giving proper weights to the various nebular filaments, yields the result 1138 ± 14 A.D.[21] Thus there is a difference of 84 ± 14 years between the dates of appearance of the nova and initial expansion of the nebula. The discrepancy, however, probably is less real than apparent, for its involves the basic assumption of a strictly uniform expansion of the nebula during an interval of nearly nine hundred years. Since there is no reason a priori why the motion should be precisely constant, we are more inclined to view the difference between the two dates as an indication that the nebular material has moved outward with a small acceleration. While the latter could, of course, be estimated from Duncan's measures by a suitable solution that includes a term in the square of the time, we feel that it would be best to defer such a calculation until a definitive set of measures is available from Baade's remarkable photographs (unpublished) of the Crab Nebula in red light. Since these pictures reveal a wealth of fine structure in the nebular filaments, it is to be expected that measurement of them on two sets of such plates, separated in time by a suitable interval, will yield results of a much higher order of accuracy for the angular expansion. The question of an acceleration in the expanding gases may then be examined with some expectation of obtaining a definite answer.

We conclude this article by considering, from a purely logistic point of view, the various arguments in favor of identification of the Crab Nebula with a supernova in 1054 A.D.

If the object observed by the Orientals in 1054 be considered by itself, there are three possible inferences as to its nature: it may have been a comet, an ordinary nova, or a supernova. By elimination, the first two possibilities may be dismissed. In the first place, the object could not have been a comet, for it re-

[21] A. N. Deutsch and V. V. Lavdovsky (*Pulkova Obs. Circ.*, No. 30, p. 21, 1940) find a time interval since outburst of 785 ± 140 years from plates taken 43 years apart.

mained in the same place among the stars for nearly two years. In the second place, it could not have been an ordinary nova, because there is no star now known in the position of the 1054 object which has the properties of a common nova in the post-nova stage. A normal nova that attained a maximum apparent brightness of —5 should be visible at the present time as a very early B- or O-type star[22] of apparent magnitude from +3 to +8,[23] depending upon its maximum luminosity. Thus there remains the supernova possibility, which is supported by a comparison of the rate of decline in light of the 1054 guest-star with that of the modern supernova observed in IC 4182.

If the Crab Nebula be regarded on its own merits, there are four possible conjectures as to its proper classification: it may be a diffuse nebulosity, a planetary, a nebulous envelope around a normal nova, or the remnant of a former supernova. The first two possibilities may readily be set aside because of the character of the bright lines in the spectrum of the Crab Nebula; the emission lines are so widely double near the center of the nebula,[24] and therefore indicate so large an expansion, that the Crab Nebula at once becomes a unique object, having no spectroscopic counterpart among all the known diffuse or planetary nebulae. The third possibility, that the nebula may be an expanding gaseous shell around a normal nova—like those seen around Nova Persei (1901) and Nova Aquilae (1918)—may also be discarded by a cogent argument advanced by Baade,[25]

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[22] Humason, *Ap. J.*, **88**, 228, 1938; *Mt. W. Contr.*, No. 596.

[23] Baade (*op. cit.*, p. 302) states that the mean amplitude, that is to say, the magnitude-drop from maximum to the post-nova stage, is of the order of 9 mag.; McLaughlin (*Pop. Astr.*, **47**, 545, 1939) concludes that the same quantity is closer to 11 mag. We have accordingly used a value of 10 mag., and have increased the range toward the fainter magnitudes by 1 mag. The largest known amplitude is 14 mags.—that for Nova Persei 1901, which also attained the highest luminosity among common novae. According to McLaughlin's compilation, the range in the amplitudes is due almost entirely to the dispersion in the maximum luminosities, since a number of ordinary novae have nearly the same apparent magnitudes before and after outburst.

[24] Mayall, *Pub. A.S.P.*, **49**, 104, 1937.

[25] *Op. cit.*, p. 304.

that the "Crab Nebula stands apart because of the unusually high luminosity (presumably the mass) of the shell. Indeed, it is more than doubtful whether the expanding nebulosities around the two novae just mentioned will be visible at all eight hundred to nine hundred years after their outbursts." Thus, by this process of elimination, there is left only the possibility that the Crab Nebula originated in a supernova outburst.

If we now recall the practical identity in position of the 1054 object and of the Crab Nebula, and the result from the modern expansion measures that the nebula began to expand at about the time the 1054 guest-star appeared, then the addition of these facts to the independently deduced supernova character of both objects makes an exceedingly strong case for the hypothesis of a common origin for both objects.

Finally, when we use what appears to be a reasonable distance-estimate for the nebula, and combine it with an apparent magnitude for the 1054 nova derived from the Chinese records and from the behavior of modern supernovae near maximum, it is found that the ancient nova's maximum luminosity probably was of the order of $-16\frac{1}{2}$ mag. Since this figure nearly matches the highest known absolute magnitude for other supernovae, we are led to the conclusion that *The Crab Nebula may be identified with the 1054 supernova,* which also probably was one of the brightest supernovae on record.

It is a pleasant duty to express our gratitude to Dr. W. Baade, of the Mount Wilson Observatory, for the use of his unpublished material on supernovae, and for numerous helpful suggestions elicited in correspondence with him.

LICK OBSERVATORY
MOUNT HAMILTON, CALIFORNIA

LEIDEN OBSERVATORY
LEIDEN, HOLLAND
November 1941