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THE CRAB NEBULA, A PROBABLE SUPERNOVA

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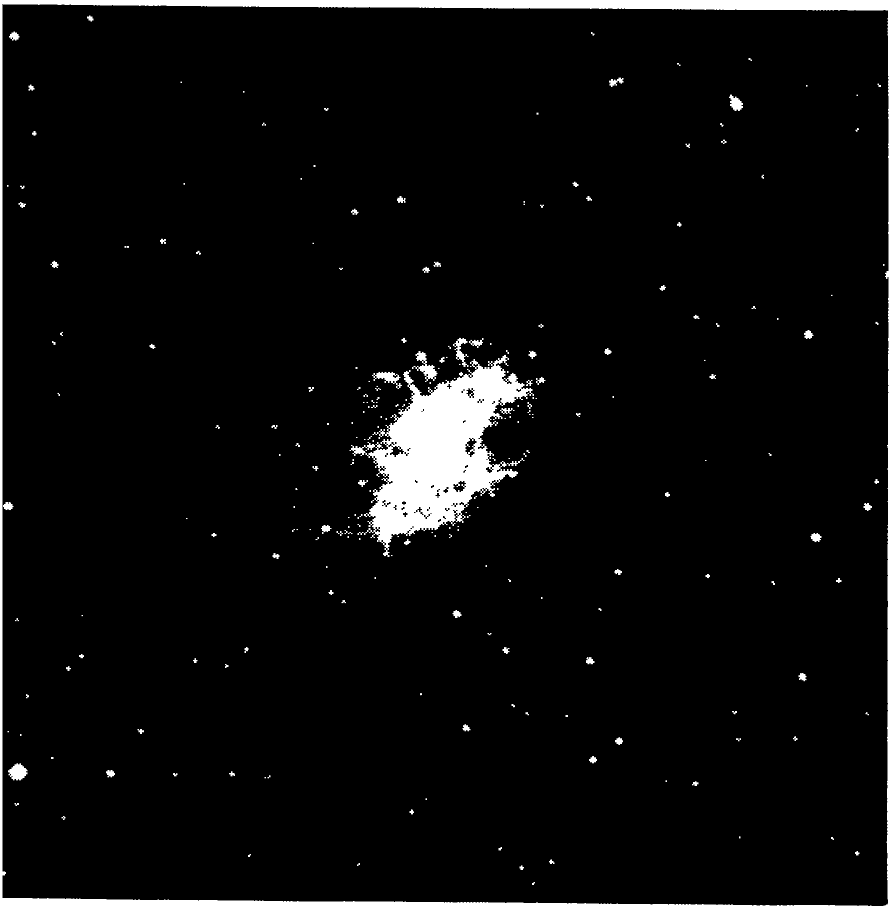
In the year of our Lord 1054, when Omar Khayyam was a small boy, and the Battle of Hastings still twelve years in the future, an unknown Chinese astronomer, perhaps weary and sleepy after working all night, was astonished to see a strange and brilliant new star appear in the greying eastern sky just before sunrise. The object was located in the Chi-



The Crab Nebula in Taurus, photographed with the Crossley reflector of the Lick Observatory. Exposure made on a red-sensitive plate.

nese stellar division of Peih, which we know as the constellation of Taurus (The Bull), a little less than halfway from the center of Peih, the Hyades, toward Pih Ho, the Twins, Castor and Pollux. Although this noteworthy astronomical event occurred on the Fourth of July, and the Chinese probably had a plentiful supply of firecrackers, it was not appropriately celebrated, so far as we know. Instead, the astronomer carefully noted the new star's approximate position with respect to a familiar star, Teen Kwan, known to us as the third magnitude star Zeta Tauri, and during the next six months watched it fade to invisibility.

By one of those remarkably fortunate coincidences, a Japanese astronomer, also unknown, witnessed the apparition of the same strange star. In addition to describing its place amongst the known stars, he recorded that it was as bright as the planet Jupiter. As we shall see in a later paragraph, this brightness estimate is a datum of crucial importance.

When the strange new star disappeared from view in the middle of the Eleventh Century, the two records of its temporary appearance likewise dropped from sight, and they remained hidden in the Oriental chronicles for nearly 900 years. In fact, these Chinese and Japanese observations did not come to the attention of modern astronomers until 1921 and 1934, respectively.

We now turn our attention from the apparition of the temporary star of 1054 to the discovery and history of the Crab Nebula, which lies quite near Zeta Tauri. Several authorities credit its first discovery, in 1731, to John Bevis, an English physician, whose avocation was astronomy. The original source is obscure, however, and his find apparently escaped the notice of contemporary astronomers, since an addition to the small group of sixteen nebulae known at the time presumably would have been received with considerable interest.

After Bevis' little-known discovery, the Crab Nebula apparently remained unobserved until 1758, when it was re-discovered by Charles Messier, a French astronomer so renowned for finding comets that Louis XV nicknamed him the "ferret of comets". Characteristically, Messier found the nebula while following the Comet of 1758—the year in which Halley's Comet also appeared and fulfilled the bold and brilliant prediction of the astronomer whose name it bears. Later, Messier discovered about 100 more nebulous objects, and collected them into the first extensive catalogue of nebulae, in this manner directing attention to them, with far-reaching results. Since the Crab Nebula is the first nebula in the first important catalogue, it enjoys a unique distinction amongst the thousands of nebulae now known.

The next significant observational records of the Crab Nebula are those of Sir William Herschel. Although his first known observation of the nebula was made in 1783, when Messier's catalogue was available, it is uncertain whether he independently discovered the nebula, or already knew of its existence. At all events, he carefully examined the nebula nine times between 1783 and 1809, and finally concluded, "As all the observations of the large telescopes agree to call this object resolvable, it is probably a cluster of stars at no very great distance beyond their gaging powers." Somewhat later, his son, Sir John Herschel, came to the same conclusion, now known to be false, but which more than 100 years ago seemed consistent with the best visual observations.

During the middle and latter half of the Nineteenth Century, the Crab Nebula was observed by many astronomers, some of whom made drawings of it. Sometime within this interval of intensive visual work, the nebula received the name by which it is now known. While it cannot be traced with certainty, it is more than likely that the original association of the word "crab" with the nebula is due to Lord Rosse who, in 1844, published a rather startling drawing of the nebula, and four years later referred to it as the "crab nebula", although his sketch more readily suggests some species of bug rather than a crab. Nevertheless, the description chosen by him apparently met with general acceptance, for it has clung to this object for nearly 100 years with a tenacity commendable in any normal crab.

The development of astronomical photography toward the end of the last century revolutionized the study of nebulae, and in the special case of the Crab Nebula, the application of photographic methods yielded results that have virtually placed this object in a class by itself. The first photograph of it was obtained in 1892 by Isaac Roberts, who was quick to notice that the nebula hardly resembled any of the existing drawings. Later photographs by Keeler, Curtis, Ritchey, and others, then established the significant fact that the roughly oval form and peculiar filamentary structure of the Crab Nebula had no faithful counterpart amongst the thousands of known nebulae.

During the first two decades of the Twentieth Century, the Crab Nebula was photographed a number of times at several of the larger observatories. Consequently there were available several series of plates for comparative study. Now the comparison of plates exposed on the same object on different dates, in order to find out whether any changes have occurred, is a very common astronomical practice that often gives valuable information. While examining some of the Lowell Observatory negatives in this manner, Lampland discovered, but did not measure, certain motions within the Crab Nebula. The much more difficult task of determining by actual measurement the nature of these motions was soon undertaken by Duncan, who used two Mount Wilson Observatory plates taken 11½ years apart. He selected twelve of the more conspicuous filaments distributed around the edge of the nebula, and measured their positions with respect to surrounding stars on each plate. The results showed that each filament had moved in a direction generally outward from the center of the nebula. In other words, the very important fact emerged, in 1921, that the Crab Nebula is *expanding*.

About the same time that the expansion of the Crab Nebula became known, the Swedish astronomer, Lundmark, using material extracted from existing translations of old Chinese chronicles, published a list of suspected temporary stars seen in ancient times. In this paper, he remarked, amongst other things, that several suspected strange stars were located in parts of the sky where there were known nebulae. One of the objects listed, already referred to, was the strange star first observed by the Chinese on July 4, 1054. While Lundmark pointed out that its position in the sky agreed closely with that of the Crab Nebula, he did not, of course, in the absence of other data, suggest any closer relation between the two objects.

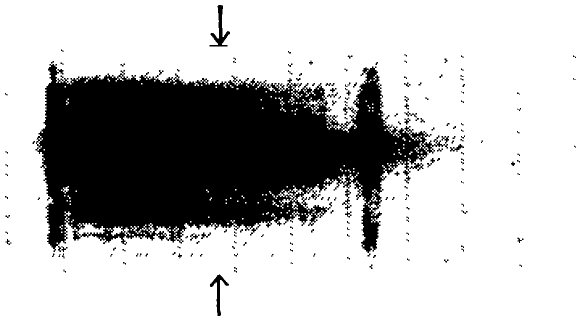
With the knowledge of the expansion measures and of the old Chinese observation of 1054, there was now available some tangible evidence to consider seriously the hypothesis that the Crab Nebula originated as a "nova" (see Leaflet No. 14), and this possibility undoubtedly occurred to many astronomers, despite the fact that published references to it are brief and inconspicuous. The inference must not be drawn, however, that the idea of an expanding nebula being related to a nova was one which was suggested solely by the observations of the Crab Nebula, because, in several recent novae, in particular, Nova Persei (1901) and Nova Aquilae (1918), expanding nebulosities were seen to surround them some time after their outbursts. In each of these cases, of course, the date when the nebula began to expand was known, but had it been unknown, it would have been possible to calculate it from the measured rate of expansion. For it is easy to see that the size of the nebula divided by its annual rate of increase gives the time interval since it began to expand, although in this case it has to be assumed that the rate of expansion has remained constant. The result of such a calculation for the Crab Nebula was briefly mentioned by Hubble in the Leaflet for January, 1928, of this series, where it was stated "the nebula is expanding rapidly and at such a rate that it must have required about 900 years to reach its present dimensions."

Hubble's conclusion did much to strengthen the case for an identification of the nebula with the old nova, for it was now evident, within the errors of the observations, that (1) the nebula began to expand at about the same time the old nova was seen, and (2) both objects were in the same part of the sky. It must be emphasized, however, that these facts by no means established the identity; they only justified a presumption in its favor until additional data became available. The problem remained in this state of partial solution until 1934, when the Japanese astronomer, Iba, published a translation of the ancient Japanese record, previously referred to at the beginning of this Leaflet. It is evident that this confirmatory observation materially reduced the uncertainty inherent in the identification.

Up to this point we have based our discussion of the Crab Nebula upon information obtained without the aid of the spectroscope — the astronomer's most indispensable implement for analyzing the light from celestial objects. Since the spectroscope provides certain important data that cannot be obtained in any other manner, we shall now consider the results of its application to the particular problem of photographing the spectrum of the Crab Nebula.

The first spectroscopic observations of the nebula were made in 1913-15 at the Lowell Observatory by V. M. Slipher, who found the spectrum to be of the type characteristic of an incandescent gas; that is, the light is concentrated into a few colors or bright lines, similar to, but not identical with, the radiations emitted by ordinary neon and helium advertising signs. However, the most interesting facts were (1) each bright line was split into two components, and (2) the separation between the two components was different in different parts of the nebula. A few years later Sanford at the Mount Wilson Observatory confirmed the first of these results with a spectrogram exposed a total of 48 hours. In each case the spectrum as photographed referred to only a small part of the nebula, with the result that it was difficult to interpret the varying separation of the double bright lines.

When the spectrum of the nebula as a whole was eventually obtained—at the Lick Observatory in 1937—the peculiar behavior of the double bright lines could readily be accounted for; it is merely the consequence of the expansion of the nebula. To understand how this comes about, it is necessary to recall Doppler's principle for a source of light moving in the line of sight. This famous proposition states that, for a luminous object coming toward the observer, any lines in its spectrum will be decreased in wave length, and, conversely, for one going away, they will be increased. Now the Crab Nebula probably is expanding in all directions from its center, and if we record its spectrum at that point, the part of the nebulosity on the near side will be approaching the observer, and its spectrum lines will be decreased in wave length, while, on the other hand, the part on the far side will be receding, and its spectrum lines will be increased in wave length. In other words, a normally single bright line will be split into two parts, and, most important of all, the separation of them will be a measure of the linear speed of expansion. Moreover, if the slit of the spectrograph is long enough to extend entirely across the nebula, we should expect the bright lines to be bow-shaped, that is, they should be double near the center of the nebula, gradually coming together at its edges. The reason for this is, of course, that at the center of the nebula the motion of expansion is mostly *in* the line of sight, while at the edges it is predominately *across* the line of sight. The spectrum



The spectrum of the Crab Nebula, reproduced from a *negative* print. Arrows mark the strongest bow-shaped double line, which is produced by oxygen atoms. Wave lengths increase toward the right.

of the Crab Nebula taken at the Lick Observatory shows just this phenomenon, for the bright lines are very noticeably bowed, or lens-shaped.

We should note, at this point, that in 1934, three years before the Crab Nebula was spectroscopically observed at the Lick Observatory, Humason at the Mount Wilson Observatory photographed the spectrum of the nebula expanding around Nova Persei (1901). In this very remarkable and striking spectrum, the lines are also bowed, being double at the center and single at the edges. Hence the resemblance between the spectrum lines of the two objects may be taken as further evidence of a relation between the Crab Nebula and a nova.

Finally, the spectrographic measures also can be used to give some very valuable information about the distance of the nebula, if the assumption is made that it is expanding at the same rate in the line of sight as it is across the line of sight. This is done, in principle, as follows: the maximum separation of the components of the double bright lines, when expressed in the proper units, is the *linear* velocity of expansion (in *miles* per second), while the rate of increase in size of the nebula, obtainable from Duncan's measures, is the *angular* velocity of expansion (in *seconds of arc* per year). As soon as any quantity, in this case the velocity of expansion, is known in both linear and angular measure, a very simple calculation gives the distance. In this manner, we estimate that the Crab Nebula is about 5000 light years from the earth.

Although this determination of the distance is subject to considerable uncertainty, being based upon several unavoidable assumptions, it appears to be the best that can be derived from the available material, and probably is not too far from the truth. If this is the case, the Crab Nebula at once becomes a unique object, because, instead of being regarded as the product of an ordinary nova, it must be seriously considered as the remnant of a "supernova" (see

Leaflet No. 88). This inference follows from the distance estimate of 5000 light years, and from the Japanese brightness estimate of the object seen in 1054, the combination of the two data yielding the intrinsic brightness of the old nova. The calculation indicates that the old nova of 1054 was at least 100 times as luminous as an ordinary nova.

In conclusion, it may be said that the identification of the Crab Nebula as a former supernova possesses a degree of probability sufficiently high to warrant its acceptance as a reasonable working hypothesis. Bearing this in mind, together with the fact that supernovae are very rare and puzzling objects, about which little is known, perhaps we can appreciate why the Crab Nebula is one of the most interesting objects in the sky.