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INVITED REVIEWS

An earlier explosion date for the Crab Nebula supernova

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Abstract The Chinese first reported the Crab Nebula supernova on 1054 July 5. Ecclesiastical documents from the near east reported it in April and May of 1054. More than 33 petroglyphs made by Native Americans in the US and Mexico are consistent with sightings both before and after conjunction with the Sun on 1054 May 27. We found a petroglyph showing the new star close to Venus and the Moon, which occurred on 1054 April 12 and April 13, respectively. Collins et al., using the four historical dates, derived a light curve that is like that of a Type Ia supernova. The only remaining problem with this identification is that this supernova was near maximum light for 85 d, which is unlike the behavior of any known supernova.

Key words: celestial mechanics — history and philosophy of astronomy — stars: supernovae: individual (Crab Nebula)

1 INTRODUCTION

The Crab Nebula (M1, NGC 1952) was named by Lord Rosse (1844) because of its appearance in his 1.8 m telescope with inferior resolution. It shows two features (Baade 1942) as seen in Figure 1 from the Hubble Space Telescope: a red filamentary structure best seen in the optical region in Hα radiation and a continuous blue emission best seen in the light between the emission lines. The latter, sometimes called amorphous radiation, was attributed by Shklovskii (1953) to synchrotron radiation caused by ejected electrons from the central neutron star moving in a dense medium. Not seen in Figure 1 is the Crab Nebula pulsar (PSR B0531+21) at the center. The elongated shape of the nebula is probably due to the interstellar magnetic field being parallel to the Galactic equator so charged particles can move more easily in that direction, according to Münch (Scargle 1967).

Lampland (1921) at Lowell Observatory first noted motion of the filaments and Duncan (1921) at Steward Observatory showed that they were moving primarily radially. Hubble (1928) first suggested that the Crab Nebula is the remnant of the 1054 supernova. Duncan (Mayall & Oort 1942) had derived an explosion date of 1172 AD while Deutsch & Lavdovsky (1940) determined the origin to be in 1138 AD. The best determination to date of the expansion rate is that by Trimble (1968), who measured the proper motions of 132 filaments on photographs taken by Baade during 1939–1966; she derived an explosion date of 1140±10 AD if one did not allow for acceleration or for curvature of charged particles due to magnetic fields and turbulence. In addition the filaments are irregular in shape and a uniform expansion may not be appropriate. Therefore the initial date could be consistent with the Chinese explosion date of 1054.

The Chinese, especially, and Japanese kept careful records of the occurrence of new stars and comets during the past 2000 years because they felt that those affected human activity. From those records Lundmark (1921) listed 60 "new stars" seen between 134 BC and 1828 AD. Among those, No. 36 in his list was first seen on 1054 July 5 near ζ Tauri. The data on that object in *Wen-Hieng-Tong-Kao* by Ma-Tuan Lin have been translated by Biot (1843). According to Biot, the guest star of 1054 AD was first seen on 1054 July 5 (Clark & Stephenson 1977). The *Sung-shih* ("History of the Sung Dynasty") stated, according to Biot: "In the 1st year of the period *Chih-ho* [1054], the 5th moon, the day *chi-ch'ou* (July 5) [a guest star] appeared approximately several inches south-east of *T'ien-kuan* [ζ Tau]. After more than a year it gradually became invisible." The Chinese stated that it

* Deceased, 2016 June 7.

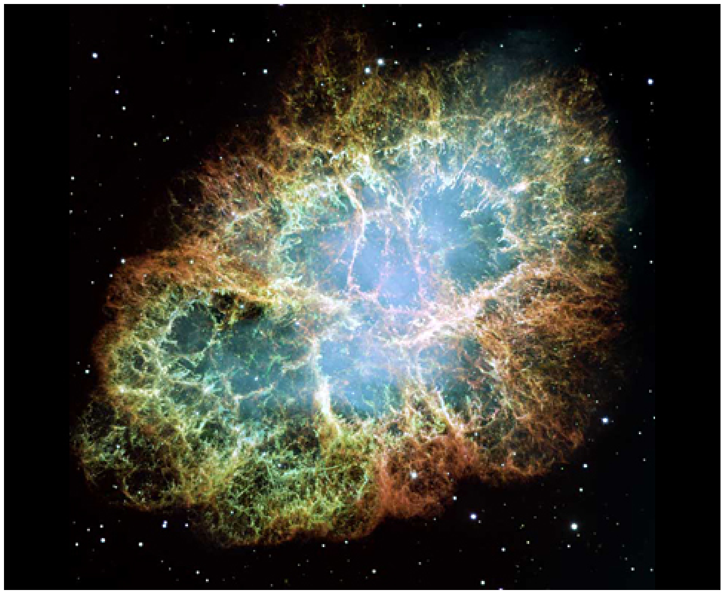

Fig. 1 A Hubble Space Telescope color picture of the Crab Nebula showing the red filamentary structure and the blue amorphous synchrotron radiation. Picture courtesy of NASA.

Fig. 2 A picture of White Mesa in the background and US 160 in the foreground. Travel on the highway is allowed for all, but non-Navajos are not allowed off the highway in a Navajo attempt to avoid pot-hunters looting artifacts.

was seen in daylight for 23 d and at night until 1056 April 17, 653 d after the first appearance. Its location ($<2°$ from ζ Tau, mistakenly called η Tauri by Lundmark) is now occupied by the Crab Nebula (Clark & Stephenson 1977) and the recent consensus is that the Crab Nebula is at the location of that object.

The Japanese records (Duyvendak 1942) stated: "In the middle ten-day period of the 4$^{\text{th}}$ moon of the 2$^{\text{nd}}$ year of the period *Ten-ki* [i.e. 1054 May 20–30] and thereafter, between 1 and 3 a.m., a guest-star appeared in the orbit [location] of Orion; it was visible in the eastern heavens. It shone like a comet in *T'ien-kuan* [ζ Tauri] and was as large as Jupiter." However, note that (1) the borders between constellations were not defined until recently, (2) the time given is in the middle of the night, whereas on July 5 it would be close to the Sun and not seen in the

Fig. 3 The petroglyph found by Bill Miller on White Mesa in northern Arizona in June 1953. It was as the Crab Nebula supernova and Moon would have been seen in the spring of 1054.

Fig. 4 The petroglyph found by Abt in Navajo Canyon in northern Arizona in 1954. It was as the Crab Nebula supernova would have been seen in the summer of 1054.

middle of the night, (3) these dates are earlier than July 5 in the Chinese records and (4) the Crab Nebula was in conjunction with the Sun on May 27, so something is wrong with those dates. Duyvendak (1942) noted that in May the Crab Nebula would have been behind the Sun and hence invisible. He suggested that the "4$^{\mathrm{th}}$ moon" should really have been the 5$^{\mathrm{th}}$ moon. In that case the Japanese observed it 16 to 6 d earlier than the Chinese, or about June 20–30. But if the Japanese saw the explosion two weeks earlier, why did the Chinese wait until July 5 to record it? It seems unlikely that clouds were so thick for two weeks over Kaifeng (capital of China in the Song Dynasty) to obscure a daylight supernova but not over Kyoto (capital of Japan) only 2000 km away.

Recent observations include evidence (Mayall 1962) that the gaseous filaments are expanding at a velocity of 1500 km s^{-1}, which is low relative to typical velocities of 5000–15 000 km s^{-1} for Type II supernovae (Wilson 1983).

The Crab Nebula was one of the first discovered radio sources. Its intensity, size, spectral distribution and polarization are all characteristic of synchrotron radiation (Scargle 1967). Wilson (1983) distinguishes three types of supernova remnants: the majority is shell-type, a lesser number is filled-center like the Crab Nebula and a few are a combination.

In 1969, Cocke et al. showed that one of the central stars is the pulsar PSR B0531+21. It has a millisecond period of 0.033 s, indicating its youth.

Further details about the history can be found in Mayall (1962) and about its astrophysics in Wilson (1983).

2 WESTERN HEMISPHERE DATA

One wonders why people in regions other than Asia did not record this object, which was visible in the daytime. Europe was in the Dark Ages, their people seldom recorded astronomical phenomena, and it often had long periods of cloudy weather. However, that is contradicted by European records of the supernova of 1006 and Halley's comet in 1066. In addition, the southwestern U.S. had much clearer weather and the Native Americans left many records, chipped or painted on rocks.

In June 1953, William C. "Bill" Miller, the photographer at the Mt. Wilson and Palomar Observatories, and the first author explored White Mesa (Fig. 2) on

Fig. 5 The petroglyph that John Fountain found at Sears Point, Arizona, showing a crescent Moon (*left*), Venus (*center*), and a bright or large object (*right*).

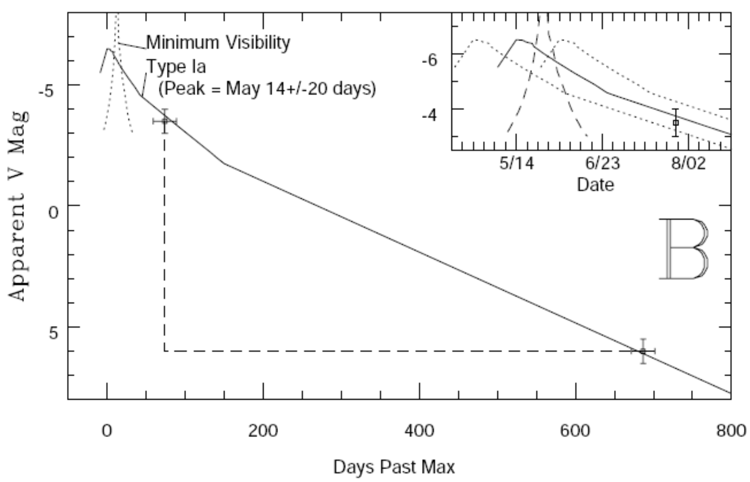

Fig. 6 The light curve derived by Collins et al. (1999) from (1) the April 1054 dates reported in seven eastern European ecclesiastical publications, (2) the 1054 July 5 date from the Chinese (Lundmark 1921), (3) the date (1054 July 27) when the Chinese last saw the new star in the daytime, and (4) the date (1056 April 17) when the Chinese last saw the new star at night. Those points fit a mean light curve for Type Ia supernovae. Reprinted from the PASP.

the Navajo Indian Reservation in northern Arizona. On White Mesa, Miller (1955) found a petroglyph (Fig. 3) that showed a crescent Moon next to a large disk. Knowing that the Native Americans rarely drew astronomical objects, he reasoned that this might represent an unusual event. Miller knew that the area had been inhabited in the 11$^{\rm th}$ century from the patterns of the potsherds we found on White Mesa. It could have been an eclipse, but eclipses at any one location are not that rare. Fred Hoyle suggested that it might represent the Crab Nebula supernova. With help from Walter Baade, Miller computed the location and phase of the Moon on 1054 July 5, using Brown & Hedrick (1919) Lunar Tables. The Moon was calculated to be within 2° of the supernova position and in a crescent phase, even though the Moon spends little time at such high declinations ($+22°01'$).

The next year while Miller and Abt explored nearby Navajo Canyon, Abt found another petroglyph showing a crescent Moon next to something bright or large (Fig. 4). However, this image looked like a reflection of the one on White Mesa. People speculated that this was simply a drawing error; the White Mesa petroglyph was a kilometer or more of rough climbing between the eastern horizon, where the event was seen, and the inside of the cave, where the first drawing was made. As a test, John Carlson (Brandt et al. 1975) asked 29 students to draw an astronomical event that they had seen two days earlier. Twenty percent drew it incorrectly.

Brandt & Williamson (1979) wrote to National Park Superintendents in the American southwest as to whether they knew of similar petroglyphs. Together with Mayer (1979), 21 more similar images were found. Fountain (2000) found 10 more in the U.S. southwest and northern Mexico. These were roughly divided between ones looking like Figure 3 and like Figure 4. Figure 3 is like what would have been seen in the spring of 1054 and Figure 4 is like what would have been seen in July 1054.

The second author (Fountain, as described in Fountain & Abt 2006) explored the astronomical situation in April 1054. He found that a crescent Moon was 3° east of the new star on 1054 April 13. Furthermore, on the previous day the crescent Moon was 1.3° west of Venus. Among archeologists, the accepted symbol for Venus in petroglyphs is an outlined cross. He found a petroglyph (Fig. 5) at Sears Point in Arizona showing a crescent Moon, Venus and a bright object all in a line.

3 EUROPEAN AND NEAR EASTERN RECORDS

In a superb scholarly study of European and near eastern ecclesiastical documents from the $11^{\rm th}$ and later centuries, Collins et al. (1999) found seven references to a new bright star seen between April 11 and May 20, i.e. in the evening sky before the Crab Nebula was in conjunction with the Sun on May 27. On May 20 the new star, visible in the daytime, was 7° east of the Sun where the new moon was located. Of particular interest was the reference (Brecher 1978; Guidoboni et al. 1992) to an account by the Iraqi physician Ibn Butlān as recorded by Abī Uşaybi'a to a new bright star seen in the daytime on 1054 April 11 during a plague in Egypt and Constantinople. These many observations lay to rest the idea that the Europeans did not see the supernova because of bad weather and did not record their observations.

This leaves two dilemmas that cannot be fully resolved at this time: (1) why did the Europeans fail to record the supernova in June-July in the morning sky after its conjunction with the Sun and (2) why did the Asians fail to record the supernova in the evening sky in April-May before the conjunction? We can only surmise that the answers may be due to superstitions and politics of the time.

Why are these dates important? Because they are used to determine the shape of the light curve which helps define what type of supernova occurred.

As described in considerable detail by Collins et al. (1999), there was an attempt in 1054 to combine the Roman Catholic Church, centered in Rome, with the Eastern Orthodox Church, centered in Constantinople. After many months of negotiations they announced on July 16 their failure to agree; it was called the Eastern Schism. We can only surmise that they thought that a new star in the heavens, easily visible in the daytime, was a condemnation by God for their failure to come to an agreement.

As to why the Chinese failed to record the "new star" in the evening sky in the spring of 1054, there is a different supposition. In China a "guest star" was considered to be a prediction that there would be a new emperor or dynasty. Furthermore, the emperor's favorite concubine died in the spring so he was in a bad mood. One can guess that even if the Chinese astronomers saw the guest star in spring, they would be reluctant, at the risk of their lives, to tell the emperor, knowing that that area of the sky would soon disappear behind the Sun. Then, maybe, they thought that the new star might not be there after conjunction. Although millions of people would have seen the guest star in the daytime, the Emperor, being shielded from the people, may have been aware of only what these advisors told him. But the new star was there in July, they told the emperor and he died the next year. We do not know what happened to the astronomers.

4 WHAT KIND OF SUPERNOVA WAS IT?

Collins et al. (1999) collected the dates (their table 1) when the new star was seen in 1054 and later. First, those included the seven dates in April and May, starting with April 11. Assuming that a daytime star had a brightness of $V = -5$ or brighter, and using the Miller (1973) determination of reddening to it from photometry of some of the filament lines, the corrected brightness was $V \sim -7$ mag. Second, we have the July 1054 date, giving approximately the same estimated brightness. The third point on the light curve is the date (July 28) when the Chinese no longer could see it in the daytime, giving about $V = -3.5$ mag. The fourth point is the date (1056 April 17) when it could no longer be seen at nighttime and therefore about $V = 6$ mag. Collins et al. (1999) derived a light curve (Fig. 6) from those four points. It fits that of a typical Type Ia supernova.

Trimble (1973) derived a distance of 1930 pc for the Crab Nebula supernova, leading to a peak absolute magnitude of $M_V = -19.9$, which is roughly the same as that derived by Hillebrandt & Niemeyer (2000) of $M_V = -19.30 \pm 0.03 + 5\log(H_0/60)$ for Type Ia supernovae.

van den Bergh (1973) argued that the expansion speed of the Crab Nebula agrees better with those of Type Ia than Type II supernovae.

However, this does not solve all of the problems with its identification as a Type Ia supernova. It is thought that Type Ia supernovae do not leave neutron stars. Zimmerman (1998) argued that the mass of the filaments is too small and the composition is not typical for a Type Ia supernova.

On the other hand, it has been proposed by King et al. (2001) that an alternative formation mechanism of supernovae is the merger of two CO white dwarfs that produces a Type Ia supernova and a magnetar. They also explain the objections to a model of the complete destruction of a white dwarf in a binary with a non-degenerate star. They estimate that many, if not most, supernovae are formed with the former mechanism.

Thus we have:

(1) The light curve fits Type Ia supernovae.
(2) The absolute magnitude at maximum light is approximately that for Type Ia supernovae.
(3) The expansion speed fits that of Type Ia supernovae.
(4) Although the conventional model for Type Ia supernovae is the complete destruction of a white dwarf in a binary system with a non-degenerate star, there are objections to that model. Instead, Type Ia supernovae may be formed by a merger of two white dwarfs, which would result in a gaseous remnant and a neutron star.
(5) The composition may not be typical of a Type Ia supernova.
(6) The Crab Nebula supernova was near maximum brightness for about 85 d, whereas other supernovae stay near maximum brightness for $<$20 d.

On balance, the Crab Nebula may be the result of a Type Ia supernova, although its existence near maximum light for 85 days makes it unusual.

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