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The Crab nebula and other historical supernova remnants

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Abstract. We outline briefly what is meant by the phrase 'historical supernovae" and how objects described by it have been identified. The history of the discovery and study of the Crab nebula are reviewed, with emphasis on recent developments in its relationship to other supernova remnants and the structure of its jet.

Key words : historical supernovae—Crab nebula

1. The historical supernovae

The enormous stellar explosions called supernovae are sufficiently rare that none has definitely been spotted in our own Milky Way galaxy since the invention of the telescope. Thus students of the subject must either confine their attention to enormously distant extragalactic events and galactic remnants of unknown age or else turn to the writings of pretelescopic civilizations in search of dateable and locatable galactic supernovae. The events thus identified are the historical supernovae and number about eight.

From the earliest times of which we have any record, humans have watched the sky and attempted to interpret what they saw. Sometimes, their motives have been ones we share—keeping the calendar in step with the sun and moon, or deciding when to plant the corn. More often, perhaps, they had in mind what we would now call astrology—attempting to predict or even control terrestrial events on the basis of celestial configurations. As a result, they did not usually record precisely the information modern astronomers would like to have and in the form we would like. So what one really means by 'historical supernovae' is that you have to be something of a historian to interpret the data.

Not all civilizations have contributed equally to our knowledge. In particular early Indian literature has gone so far essentially unexamined for this purpose, and may well harbour a wealth of reports of new stars as well as comets, eclipses, planetary conjunctions and other astronomical phenomena. On the other hand, the most thoroughly searched literature of all, that of classical Greece and Rome, contains no certain records of any new stars (novae or supernovae) at all. The mediaeval European chroniclers reported the very bright supernova of 1006, and renaissance scholars provided enough details of Tycho's (1572) and Kepler's (1604) supernovae to permit the reconstruction of approximate light curves (Clark & Stephenson 1977). Babylonian and Arabic records have been only partially examined, the former yielding no convincing new stars, and the latter a number of accounts of SN 1006 and a single reference to SN 1054.

The most productive investigations have been those of the Chinese (and to a lesser extent Japanese and Korean) astronomical literature. This has happened because, from the time of the Han dynasty (202 BC–220 AD) onwards, an astronomical bureau formed a subdepartment within the Ministry of State Sacrifices. Its two main functions were those alluded to above—maintenance of an accurate calendar and observation and interpretation of celestial portents. In addition, these records have been rather thoroughly examined by people knowledgeable in the languages and historical periods concerned (*cf.* Brecher 1985; Clark & Stephenson 1977, and references therein). Even here there are pitfalls. A great burning of books in 213 BC wiped out most of the history (and many of the historians) of what had gone before. Much of the provincial historical literature has yet to be examined for astronomical purposes (though work continues). And, finally, one must worry about both the reliability and the completeness of the available documents.

Reliability can be checked by means of solar system events whose times and directions in the sky we can now calculate. It seems to be quite good : the eclipses recorded are usually real eclipses, and the planetary positions recorded are accurate presentations of the phenomena. Figure 1 provides an example. V_1 and V_2 show the calculated positions of Venus when it was described as entering with in the mouth of the asterism *Nan-ton* (which consists of the six stars shown, now part of Sagitarius). The arrow indicates Venus' apparent daily motion, showing that the reported position is accurate enough to belong to an observation made on particular day and not two or three days earlier or later. Nevertheless, occasional grains of salt from an expert cellar are in order. For instance, many of the dynasties had particular colours closely associated with them, red for Han and T'ang, blue for Sui and Ch'ing, and a golden yellow for Shang and Sung. Reports of new stars in the reigning emperor's own colour are therefore suspect (including the often-quoted description of the 1054 events as "yellow and favourable to the emperor").

Completeness is more difficult to assess, since we need to ask precisely whether absence of evidence is evidence of absence. An indirect argument comes from the temporal distribution of events recorded through a dynasty. Solar eclipses, needed for calendric purposes, were reported at a roughly constant and correct rate of 3 or 4 per decade throughout the Chin dynasty (*c*. 260–520 AD). But as figure 2 shows,

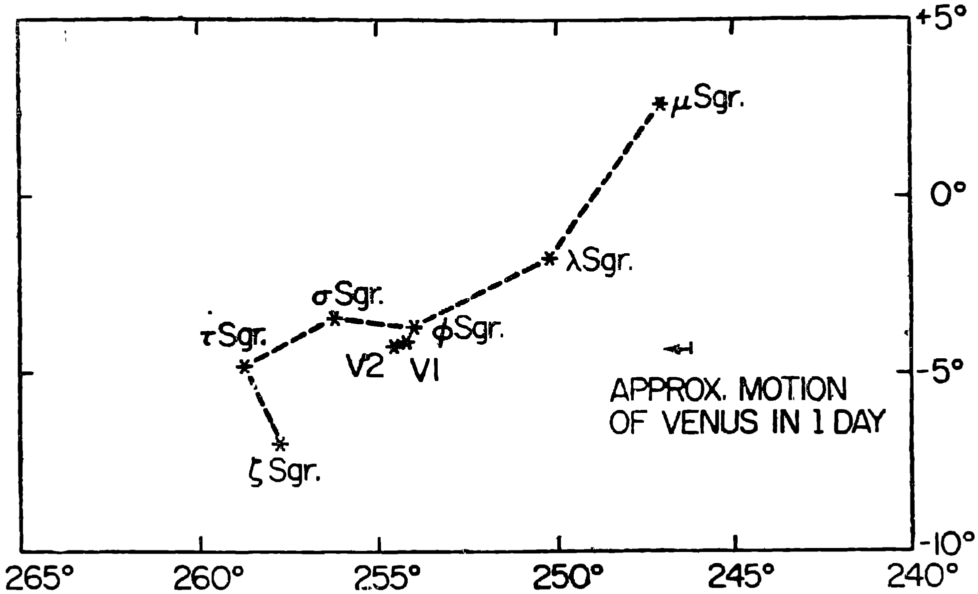

Figure 1. Calculated positions of Venus on two dates (V_1 = 117 Oct. 23; V_2 = 125 Oct. 24) when it was described as entering within the mouth of *Nan-ton*, the asterism consisting of the six stars from Sagitarius shown. Given the amplitude of Venus' apparent daily motion, it is clear that the description is sufficiently precise to constrain the observation to within $\pm$ 2 days. This suggests that the Chinese records are typically quite reliable.

the situation for astrologically important phenomena is different. These phenomena include solar halos, sunspots, daylight sightings of Venus, and assorted conjunctions and occultations of planets with the moon, with each other, or with asterisms. Almost none of these turn up during the early, 'honeymoon', portion of the dynasty, while toward the end, as discontent increased, the omen rate increased to more than 50 per decade. The five candidate supernovae (indicated by stars in figure 2) all come from the latter part of the dynasty, suggesting that there may be significant incompleteness in the early years. Other selection effects apply to other historical periods, and some of them can undoubtedly be mitigated by more careful examination of the provincial records. The implication of data like those represented in figures 1 and 2 is that, if an event is reported, it probably occurred in something like the recorded form, but that no strong conclusions can be drawn from the nonreporting of an event.

Several classes of temporary 'stars' appear in the Chinese records. *Hui-hsing* ('broom stars' or 'sweeping stars') are normally tailed comets; *po-hsing* ('rayed stars' or 'bushy stars') are normally tailless comets; and *k'o-hsing* ('guest stars' or 'visiting stars') ought to include the novae and supernovae. But there are exceptions. Some k'o-hsing moved across the sky and so must have been comets. A very bright point source might have been perceived as tailed or bushy. And the 1006 event was called a *chou-po* ('Earl of Chou') star, apparently to emphasize its exceptional brilliance and auspicious nature.

We ask first of a candidate supernova that the event have remained visible for at least a month or two and that no motion has been recorded. These criteria yield

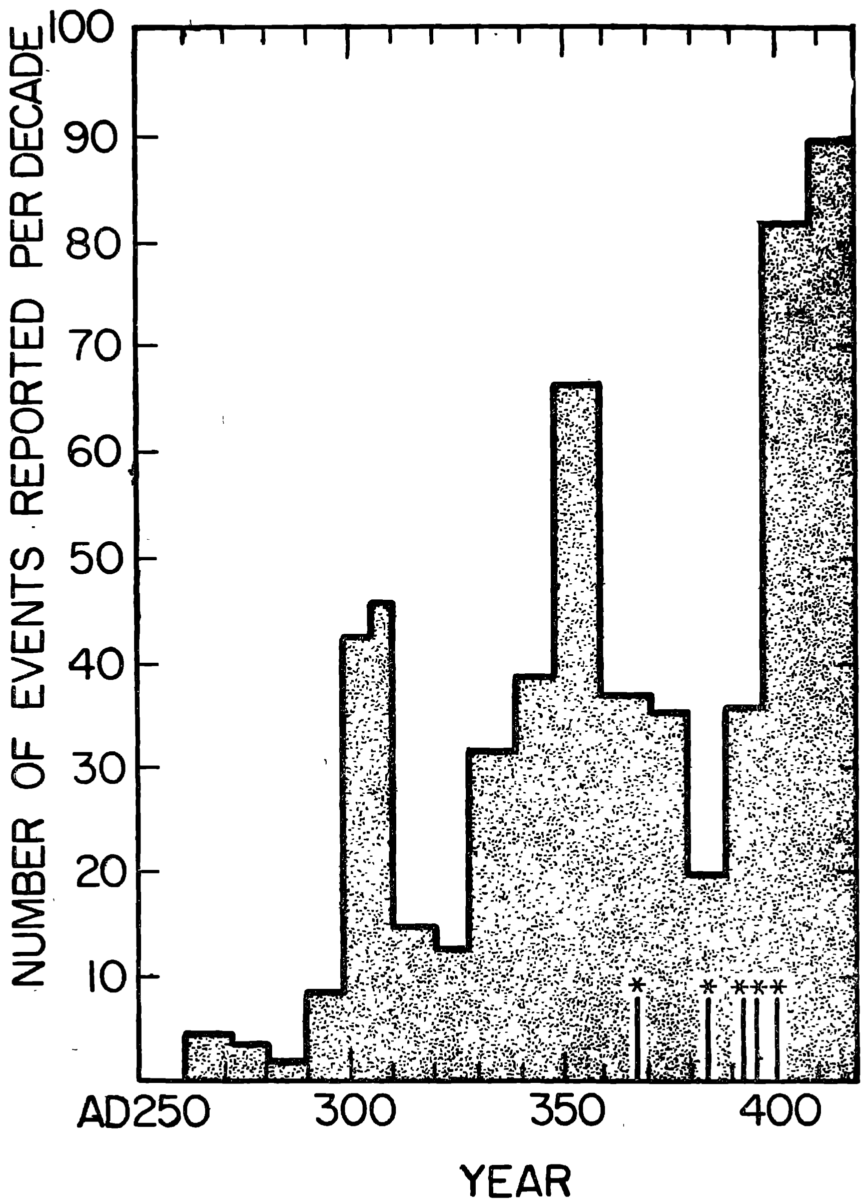

Figure 2. Rate of reportage of astrologically-interesting celestial phenomena during the Chin dynasty. The gradual increase from a few per decade during the early 'honeymoon' period to more than 50 per decade as discontent with the dynasty increased suggests that records of such events (including halos around the sun, sunspots, daylight sightings of Venus, and assorted planetary and lunar conjugations and occultations) may not always be very complete. It is perhaps significant that the five supernova candidates all date from the latter part of the dynasty.

the list of 19 events given in table 1, though the 1408 AD star was reported only once, and neither duration nor position are well specified.

Some further elimination is possible. Supernovae in spiral galaxies are largely confined to their discs (Maza & van den Bergh 1976). Thus any supernovae at galactic latitude, *b*, larger than about 25° would have had to be within about a kiloparsec of us and would have looked exceedingly bright. This means that the

5 BC and 61, 64, 70, 247, 396, and 837 AD events were almost certainly comets or novae, though it is not always possible to decide which (Clark & Stephenson 1982). 1592A may have been Mira Ceti, and the other two events of that year complete fabrications. Only Korean sightings have been found. The remaining objects are the historical supernovae, listed in table 2. Each has a remnant of roughly the same age certainly or probably associated with it.

Another handle on the completeness of the Chinese records comes from asking about young supernova remnants for which no initiating event has been identified. There are three—RCW 103 and MSH 11–54, both probably less than 1000 years old, but too far south to have been seen from China, and Cas A, whose explosion was either not seen by anybody in 1657 ± 3 (Kamper & van den Bergh 1983) or was

Table 1. New stars of long duration recorded in China (C), Japan (J), the Arab world (A), Europe (E), and Korea (K)

Date	Chinese description	Duration	Recorded in	Remarks
− 5	hui	70+days	C	Comet/nova
+ 61	k'o	70 days	C	Comet ? (motion ?)
+ 64	k'o	75 days	C	Comet ? (motion ?)
+ 70	k'o	48 days	C	b = + 45°; Nova ?
+ 185	k'o	20 months	C	Supernova
+ 247	hui	156 days	C	Comet ? (motion ?)
+ 369	k'o	5 months	C	Position unknown
+ 386	k'o	3 months	C	Supernova ?
+ 393	k'o	8 months	C	Supernova
+ 396	"star"	50+days	C	b = − 25°; Nova
+ 402	k'o	2 months	C	Comet ? (motion ?)
+ 837	k'o	75 days	C	b = + 75°; Nova
+1006	k'o	several years	A, C, E, J	Supernova
+1054	k'o	22 months	A, C, J	Supernova
+1181	k'o	185 days	C, J	Supernova
+1408	"star"	?	C	Cyg X-1 ???
+1572	k'o	16 months	C, E, K	Supernova
+1592A, B, C	k'o	15, 3, 4 months	K only	Mira; fabrication?
+1604	k'o	12 months	C, E, K	Supernova

Table 2 The historical supernovae

Date	Observer(s)	Remnant
185	Chinese	RCW 86 = G 315.4 − 2.3
393	Chinese	CTB 37A/B = G 348.5 + 0.1 or G 348.7 + 0.3
1000 ± 200	(extreme south)	MSH 11 − 54
1006	Chinese, Japanese, Europeans, Arabs	PKS 1459 − 41
1054	Chinese, Japanese, Arabs	Crab nebula*
1181	Chinese, Japanese	3C 58 = G 130.7 + 3.1
1408 (?)	Chinese	CTB 80; Cyg X-1 (both doubtful)
1572	Chinese, Koreans, Europeans (Tycho)	3C 10 = G 120.1 + 1.4
1604	Chinese, Europeans (Kepler)	G 4.5 + 6.8
1679 (?)	Flamsteed	Cas A

*Otherwise known as Messier 1, Strohmeier 40, JH 357, GC 1157, Milne 9, 4C 21.19, van den Bergh, Marschner & Terzian 8, 3C 144, NGC 1952, Hall 050211, CM Tau, 3A 0532 + 219, 4U 0532 + 21, NP 0532, H ϕ534 + 21, CGS 0531 + 219, CG 185 − 5, 2CG 184 − 05.

unexpectedly faint in 1679 (Ashworth 1980). The implication is that the completeness may be rather better than suggested by figure 2. If so, then we can put reasonable confidence in the galactic supernova rate as derived from the historical events (~ 1/30 yr, Tammann 1982; Clark & Stephenson 1982).

If the sample of table 2 is reasonably complete for events within 5 kpc and in our sector in galactocentric longitude, it also makes sense to ask how probable the clumps and gaps in the temporal distribution are. The answer (Clark 1985) is more probable than you might have guessed. A long simulation of randomly-firing supernovae in a thin-disc galaxy showed at least 10% of all millenia should have distributions as clumpy as that from 985 AD to the present.

Nevertheless table 2 leaves the impression that we are overdue for another naked-eye supernova. For generations, astronomers have claimed that, when there was another astronomer as great as Tycho and Kepler, there would be a supernova for him to see. And none of us has felt deprived at not earning that accolade. The title of 'greatest astronomer since Flamsteed' is perhaps less to be coveted.

There is a considerable literature for all the objects in table 2. But we wish to focus here on the Crab nebula, the first of the historical supernovae to be identified, and still the most thoroughly studied (though not necessarily the best understood).

2. The Crab nebula

Table 3 summarizes the history of discovery and our understanding of the Crab nebula, supernova, and neutron star. The names and dates after 1900 come largely from *Jahrsbericht* and its successor, *Astronomy and Astrophysics Abstracts*, and complete references can be found there. Most of this history is still very close to us in time and in the interconnectedness of workers in the field.

Some of the events listed now seem trivial, though they were important at the time, for instance Lassell's conclusion that the nebular emission was genuinely diffuse and not attributable to unresolved stars. The Crab was the first object for which this was firmly established. Other items, like the relatively large proper motion of the Crab's central star (first measured by van Maanen in 1928) came to seem significant only long after the event. The reality of this large velocity and the extent to which it might be shared by the nebula were still being debated in 1969 (Minkowski 1970; Trimble 1970; Woltjer 1970). Subsequent work on other pulsars has made a 100–200 km s^{-1} velocity seem likely enough, without definitely establishing whether the proper interpretation is liberation from close binary systems, asymmetry in the supernova, or something more esoteric.

Others of the items have never been properly published, including Landau's first conception of neutron stars in 1932 (described by Rosenfeld 1973) and the infrared data collected by Glaccum *et al.* (1982) using the Kuiper airborne observatory.

Two topics on which there has been considerable recent discussion deserve slightly fuller treatment than is given in table 3. These are the existence and frequency of supernova remnants resembling the Crab nebula and the properties and causes of the jet.

Table 3. Capsule history of the Crab nebula, its pulsar, and related phenomena

Date	Event
1054	Light reached earth (July 4) from explosion *c.* 5283 BC
1731	Crab nebula discovered by John Bevis
1758	Catalogued as MI (Messier)
1844	Named (Lord Rosse)
1854	Emission genuinely diffuse, not due to unresolved stars (Lassell)
1916	General relativity and the Schwarzschild solution. High velocity emission lines in the Crab (Slipher; who also very nearly looked for optical polarization, and would have probably found it, *cf.* Brecher 1985).
1920	S And (SN 1885) had $M_v \sim -15$: Crab nebula = remnant of 1054 event (Lundmark)
1921	Crab shows large proper motions, amounting to rapid expansion (Lampland); A division of the novae into two magnitude classes is 'not impossible' (Curtis)
1928	Star near centre of the Crab has large proper motion (van Maanen)
1930	Theory of relativistic, electron-degenerate stars (Chandrasekar)
1932	Discovery of the neutron (Chadwick); neutron stars (Landau)
1933 (Dec.)	Supernovae defined; energy comes from neutron star formation; some of it goes into accelerating cosmic rays (Baade & Zwicky)
1934	First neutron star models (Tolman); First supernova search (Zwicky)
1935–38	Supernovae become respectable: papers by Zanstra, McCrea, Barnothy & Forro, Hubble, Payne, Whipple, Sawyer, Humason, Popper, Mayall
1939	Neutron star models with approximate maximum mass (Oppenheimer & Volkoff); Continued gravitational collapse to less than Schwarzschild radius (Oppenheimer & Snyder); Supernovae can be used as standard candles for cosmology (O. C. Wilson); Neutrino emission a possible trigger for core collapse in massive stars (Gamow & Schoenberg)
1940	Two types of supernovae (type I and type II) can be distinguished from their spectra (Minkowski)
1941–42	First supernova review papers; Neutron stars as gravitational lenses (Zwicky); Supernova theories (Gamow, McVittie, Schatzaman)
1942	South preceding star is the remnant of 1054 event (based partly on spectral data) (Baade & Minkowski)
1948	Crab nebula identified as a radio source (Bolton & Stanley)
1950	Type I supernova light curves are powered by nuclear decays (Borst)
1952	Supernova remnants as a class are radio sources (Hanbury-Brown & Hazard)
1953	Optical synchrotron emission predicted in the Crab nebula (Shklovskii)
1954	Optical synchrotron (polarization) verified in Crab (Dombrovsky)
1956–57	Stellar implosions and Cf^{254} as supernova energy sources; photodisintegration of iron as trigger of core collapse; neucleosynthesis in stars, including e and r process in supernovae events (Burbidge, Burbidge, Fowler, Hoyle, Cameron, Christy, Baade)
1957	First Ph.D. dissertation on the Crab nebula (Woltjer); detection of radio polarization in Crab (Mayer, McCullouch & Sloanaker)
1960	Thermonuclear explosions as an energy source for supernovae (Hoyle & Fowler); Cosmic rays accelerated in supernova shocks (Colgate & M. Johnson)
1963	Identification of Crab x-ray source (Bowyer, Byram, Chubb & Friedman)
1964	Calculations of x-rays from cooling neutron star models (Morton; Chiu & Salpeter; Hayakawa & Matsuoka; Bahcall & Wolf; Tsuruta & Cameron . . .)
	X-ray source not compact (Bowyer *et al.*), requiring continuous input ot relativistic electrons
	Detection of compact, low-frequency radio source near Crab centre (Hewish & Okoye)
1965	First neutron star star review pader (J. A. Wheeler); Magnetic neutron stars (Woltjer)
1966	Momentum transport by neutrinos as ejection mechanism for type II SN (Colgate & White); Neutron stars should be detectable from x-rays emitted when they accrete gas from companions in close binaries (Zeldovich & Guseino)
1967	Rotating neutron star models (Hartle); Rotating, magnetic neutron star as possible energy source for the Crab nebula (Pacini); Sco X-1 modelled by accretion on neutron star in close binary system (Shklovskii)
(Aug.-Nov.)	Pulsars discovered (Bell & Hewish)
1968	Second Crab nebula Ph.D. thesis (April; Trimble); Discovery of pulsar in/near Crab (Staelin & Reifenstein; Comella *et al.*; October)
	Pulsar NP 0552 slowing down (Richards & Comella, November) = continuous energy input, as required (Gunn & Ostriker; Golderich & Julian, December)

(Continued)

Table 3 (*Continued*)

Date	Event
1969	South preceding star = NP 0532 (Cocke, Disney & Taylor; Nather, Warner & MacFarlane; Lynds, Maran & Trumbo). Second derivative of pulsar period (x-ray data, May, Goldwire & Michel; optical data June, Boyton *et al.*; radio data, July, Richards *et al.*) First conference devoted exclusively to Crab nebula (Flagstaff, June)
1969	NP 0532 shows timing glitches (Boynton, Growth, Partridge & Wilkinson)
1970	Discovery of Crab nebula jet (van den Bergh); Neutron star mass $\gtrsim 1\ M_{\odot}$ needed to power nebula (Trimble & Rees); First international Crab nebula symposium (Manchester, IAU Symp. No. 46)
1971	Upper limits to gamma ray flux constrain Crab magnetic field strength to roughly the equipartition value (Fazio *et al.*); 3C 58 pointed out as the first Crab-like SNR (Weiler & Seielstad)
1972	Pulsations in binary x-ray sources show that the compact object is a rotating neutron star (Gorenstein *et al.*)
1972–79	Optical and UV spectroscopy of Crab nebula show He/H $\geqslant 1$, C + N + O/H + He = low to normal (Davidson; Kirshner; Henry; Gull; Fesen; Chevalier)
1974	Pulsars are, in general, high velocity objects (Rickett; Lang; Manchester); Binary pulsar and gravitational radiation (Hulse & Taylor)
1982	Millisecond pulsars (Backer *et al.*) Crab infrared emission comes from dust which accounts for about 0.01 $M_{\odot}$ of metals and raises heavy element abundance to normal (Glaccum & Herper; IRAS) Progenitor models of 8–10 $M_{\odot}$ (Nomoto; Hillebrandt)
1984	Dynamical data on the jet (Fesen; Shull); Pulsar in the LMC, 0540–69, shows x-ray (Seward, Harnden & Helfand) and optical (Middleditch & Pennypacker) pulses at P = 50 ms, with a slowing-down timescale of 1200 yr and many other similarities to the Crab and its pulsar

Crab-like remnants, or plerions, are defined in terms of their radio properties, and, although about a dozen are known in the Milky Way (and a few more in the Magellanic Clouds), existing radio surveys have been carried out in ways that discriminate strongly against identifying them (Weiler 1985a,b). X-ray searches for compact cores in known supernova remnants (Helfand & Becker 1983) are much more complete, but they pertain only to recognized SNRs. Thus, to the extent that plerions (because of their structure and flat spectral indices) have not yet been separated out from H II regions in the radio surveys, the x-ray information does not really constrain their numbers either. The arguments of Srinivasan *et al.* (1984) and others on the rarity of formation of rapidly spinning, strongly magnetized pulsars may therefore be subject still to some modification.

The large Magellanic Cloud SNR and pulsar 0540–69.3 have recently been advanced as near-twins to the Crab nebula and 0532. They are also very nearly 90° apart in the sky, which ought to be a comfort to believers in cyclic cosmologies! Table 4 compares the objects. The numbers come largely from talks given by F. D. Seward S. P. Reynolds, J. Middleditch, R. H. Becker, and R. P. Kirshner at the 1984 October meeting on the Crab Nebula and Related Supernova Remnants (Kafatos & Henry 1985). To first order, one gets the impression that the similar properties are those dominated by the pulsar (except for pulsed radio emission), whereas those dominated by the original explosion and its interaction with the surrounding medium are different. Perhaps one should only conclude that stars of quite different masses can leave similar pulsars.

Van den Bergh (1970) first reported a luminous jet extending from the north east nebular boundary. Later work established that it emits both line (thermal) and

Table 4. Comparison of SNR 0540 – 79.3 and its pulsar with Crab nebula and NP 0532

Property	0540	Crab
Pulse period	50 ms	30 ms
dP/dt	4.79×10^{-13} ss^{-1}	4.23×10^{-13} ss^{-1}
dE/dt	1.5×10^{38} erg s^{-1}	4.5×10^{38} erg s^{-1}
Implied surface field	4×10^{12} gauss	3×10^{12} gauss
L_x (Tatal)	1×10^{37} erg s^{-1}	2×10^{37} erg s^{-1}
$L_x/\dot{E}$	0.05	0.05
X-ray size	= Optical	1/4 Optical
X-ray spectral index	0.8	1.0
X-ray pulsed fraction	23% (larger at larger photon energies)	4%
X-ray pulse shape	Sinusoidal	Sharp pulse; wider interpulse
Age from dP/dt	1600 yr	1230 yr
Optical radius	1 pc	2 pc
Doppler expansion vel.	1250 km s^{-1}	2000 km s^{-1}
Expansion age	800 yr	844 yr
Real age	800–1000 yr (?)	930 yr
L_{opt} (total)	2×10^{36} erg/sec	3×10^{36} erg s^{-1}
$(B-V)$ Colour	0.85 ± 0.35	0.5
Opt. pulsed fraction	0.6%	0.4%
L_{opt} (pulsed)	10^{34} erg s^{-1}	10^{34} erg s^{-1}
Opt. pulse shape	Sinusoidal	Sharp pulse and interpulse
Radio flux (408 MHz)	< 1 Jy	1000 Jy; 1.6 Jy at LMC dist.
Radio spect. index	0.43	0.25
Radio size, structure	= Optical; plerion	> Optical; composite
Radio pulsed flux	$< 1/2$ mJy	6 Jy; 10 mJy at LMC dist.
Remnant composition	O/H high He/H normal	O/H normal He/H high
Estimated progenitor	25–30 $M_\odot$	8–10 $M_\odot$

continuum (synchrotron) radiation and prompted countless models, invariably a bit contorted to match the undoubted fact that the axis of the jet does not point back to the pulsar position either now or did in 1054. These models will have to be rethought in the light of the observations (a) that the jet is moving outward along its own axis at about 4000 km s^{-1} (Feson & Gull 1985); (b) that it is simultaneously expanding cylindrically perpendicular to its axis at about 360 km s^{-1} (Shull *et al.* 1985); (c) that the local magnetic field is aligned with the jet (Velusamy 1985); and (d) that the jet composition is quite nearly that of the adjacent nebular filaments, including less-than-average helium enrichment (Henry 1985).

The length of the jet divided by its axial velocity and the width divided by the transverse velocity both give timescales of 600 yr. One is left with the impression that something merely punched a hole at a random weak point on the nebular surface, and the local mix of thermal and relativistic gas shot out into a less confining medium. It is probable and relevant that this jet is merely the most conspicuous of a fairly numerous class because it is bright and nearly in the plane of the sky. The velocity data of Clark *et al.* (1983) show high velocity material at several points south west and north west of the nebular centre, suggesting that we would see jets there if we happened to be viewing the object from a different angle.

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