Chapter VII - Exploding Stars

The advent of radio astronomy, with its flair for singling out the more turbulent and cataclysmic processes of Nature, has transformed the one-time view of the heavens as the ultimate in serenity, unchanging and immutable. We now know that commotion and disorder are widespread on a celestial scale, and that the heavens have seen some all-time highs in the way of explosions, certainly of stars, possibly of whole galaxies, and maybe of the entire Universe.

It is prodominantly by the light generated in stars that we see the Universe around us. Study of the stars, the multitudinous self-luminous bodies which are still pin-points of light even in the largest telescopes, has been the province of the optical astronomers. Centuries of careful work have produced a general picture of their nature and characteristics, in quite remarkable detail, considering how far away they are and the slender clues which they provide. The Sun, as we noted earlier, is relatively sedate and middle-aged, outstanding only because it is so very close on the scale of stellar distances (8 light minutes). The basic star-building material, the primordial gas clouds, appears to be uniform in composition throughout the Universe because the condensations within it which finally become stars show remarkable similarities in their chemical composition, and in their total mass. The range in sizes in relation to that of the Sun is surprisingly small: few have more than ten times its mass and few less than one-fifth. Within this limited range, however, their properties differ quite markedly. In theprocess of converting the energy of the original gas cloud into light and heat the most obvious characteristic revealed by stars is the amount of light we receive from them,referred to as their apparent brightness. The Greek astronomer Hipparchus was the first to introduce a scale of "magnitudes" in specifying the apparent brightness of stars: he divided the visible stars into five classes, the brightest being of <u>first magnitude</u> and those which could just be distinguished by the naked eye were said to be of the <u>sixth magnitude</u>

The magnitude scale for stellar brightness used to-day is based on that of Hipparchus. It is a logarithmic scale in which a range of 5 magnitudes corresponds to a ratio of 100 to 1 in brightness, the constants in the equation being chosen so that the new scale conforms to that used by the ancients. If two stars emitting flux densities S_1 and S_2 are of magnitude m_1 and m_2 respectively, then the difference in their magnitudes, $m_1 - m_2$, is given by

$$m_1 - m_2 = -\frac{5}{2} \log_{10} \frac{S_1}{S_2}$$

(the negative sign and the numerical factor 5/2 being adopted to conform with Hipparchus' scheme). The magnitude difference depends on the spectrum of the radiation being compared, <u>visual</u>, <u>photographic</u>, <u>photometric</u> and <u>radio</u> magnitude scales being those in common use. The xx visual magnitudes of some objects are as follows:

The Sun	27
Moon	12
Venus, about	4
Sirius	1.6
α Centauri	
Faintest naked eye stars	6
Faintest stars visible with 200" Palomar telescope	21

The quality of the light from a star, its spectrum, is largely determined by its surface temperature, and in the spectral classification of stars astronomers use the letters O, B, A, F, G, K, M, R, N, S* to indicate a progressive decrease in surface temperature from about 35000° for early O type to 6000° G_o (the Sun) and 3400° for M_o. The brightness or apparent magnitude of a star depends on how far away it is, and whether its light has suffered any absorption on the way; a more fundamental property of a star is its <u>absolute magnitude</u>, which is defined as the magnitude it would have if it were at a distance

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* The mnemonic used to remember this is: "Oh, be a fine girl. Kiss me right now, sweetheart."

of 10 parsecs. Absolute magnitude is thus a measure of the luminosity or total light flux emitted by a star. It is closely related to the spectrum of its light and to its mass. The range in values covers at least 20 magnitudes, from about -5 for some short period Cepheid variables, through +4.8 for the Sun to +15 for some relatively rare stars which are cooler than spectral type M. An interesting and fundamental property of stars is the relationship between their luminosity (absolute magnitude) and spectral class: this was first recognized by Herts and Russell and referred to as the H.R. or Russell diagram. This is indicated in Figure 1: the majority of stars lie in a broad band, the "main sequence" through which they progress as they gradually exhaust their full resources, but there are some which are much more luminous than the general run (the giants) and a few far below average (the white dwarfs): for these life runs a briefer and more chequered course.

The initial source of heating for a star is the compression arising from gravitational attraction of the primordial gas: at a later stage nuclear processes of increasing complexity become predominant and the subsequent history of the star is determined by the balance between the energy released within it and the extent to which this can be successfully conducted to its luminous exterior and radiated away. The Sun is typical of most stars in showing relatively stable behaviour, with only quite minor changes in comparison with its total energy output. Some, however, show significant variations, both irregular and periodic, an important group among the latter being the Cepheid variables (after , the first to be recognized) whose variation is due to an oscillation of their atmosphere, presumably under gravitational forces. The relationship between the period of the variation and absolute magnitude is so close that the apparent magnitude of a Cepheid variable provides a good indication of its distance.

Occasionally non-recurring flare-ups occur which raise the brightness of a star by 5-10 magnitudes in a period of a few days: such flare-ups are known as novae and are usually accompanied by the expulsion of a shell of gas. Still greater catastrophes can happen to stars, however, which result in their elevation to supernovae - and it was in pinpointing one of the most interesting supernovae as a prominent radio source that radio astronomy stepped beyond the solar realm and took its first important step out into the Galaxy.

When Bolton and Stanley in Sydney decided in 1947 to see whether there were any other radio stars in the skies besides the Sun they soon found several localised areas emitting radio waves which were effectively point sources. None of them coincided with bright stars but one in the constellation Taurus was so close in position to an unusual nebula, M1 in Messier's list but more descriptively known as "the Crab" because of its appearance, as to make it virtually certain that this was the origin of the radio waves. A photograph of the Crab taken with the 200" Palomar telescope appears as Plate . This much-studied object first swam into the ken of the astronomers as a result of a spectacular explosion on 4 July 1054, when from presumed invisibility it increased dramatically in brightness and "was as visible in full daylight as Venus, with spikes leaving it in all directions. Its colour was reddish-white. It was perfectly visible for 23 days". Strangely enough, there appears to be no mention of this apparition in any European chronicles. The event was not missed, however, by astrologers in the service of the Chinese emperor, and their recorded detail of this unusual "guest star" leaves no doubt that they witnessed the awe-inspiring sight of a star undergoing one of the greatest catastrophes that can befall a stellar body - the uncontrolled release of fantastic amounts of energy in its outer regions. This occurs when conditions within the core of a star are such that a pressure balance can no longer be maintained. This state of affairs can arise rather late in the life of a star comparable in size with our Sun, or much earlier for a star which is considerably more massive, and the supernovae which result are said to be a Type I or Type II respectively. In each case the explosion is an extremely violent one, with matter being ejected at speeds of over 3 million miles per hour, but the total mass involved in a Type II event is appreciably greater, of the order one or more solar masses as against one fifth of this for a Type I supernova. The visual brightness of Type I is greater than that of a Type II but the latter produces strong ultra violet emission and somewhat higher velocities of ejection, and the overall radiation from a Type II supernova is greater.

The Crab explosion is classified as a Type I explosion. After the prodigal display of energy recorded by the Chinese astrologers, during which it blazed away at a rate one hundred million times that of the Sun, it slowly faded over a period of about a year. There remains near its centre two faint stars of about the ninth magnitude which until recently were regarded as of no significance. As a result of studies with the 200" Palomar telescope Baade and Minkowski identify one of these two stars, the south west preceding component, as the remains of the core of the original explosion, and report that wispy filaments are still being ejected from it from time to time. It turns out now that this star is not only a radio source, but a "<u>pulsar</u>", one of those curious objects which emit short duration pulses of radio energy with the regularity of a superb clock. (See Chapter). For full measure it has recently been found to emit <u>light flashes</u> in synchronism with its radio pulses.

Messier thus showed remarkable insight in selecting the Crab to head his list of prominent nebulae (M1): it has been of continuing interest to optical astronomers ever since. Photographs of its spectrum have shown a strong background continuum but with a superposed emission spectrum of hydrogen, together with forbidden lines of oxygen and nitrogen, i.e. the characteristic spectrum of interstellar matter. The lines, however, are doubled about their normal position, ~~indicated~~ indicative of Doppler effects. The amount and direction of the displacements show that one set of lines, from the filamentary structure in front of the nebula, is approaching at a speed of some 1100 km/sec (over 2 million miles per hour) while the other set, from behind the nebula, is receding at the same high speed. The effect of the original explosion is thus still continuing: on the assumption that the expansion has proceeded symmetrically for the past 900 odd years we can obtain an approximate estimate of the nebula's distance from the fact that it is now about 4 minutes of arc in diameter. This turns out to be about 1100 parsecs, or 4000 light years. Alternatively, we can work backwards from the present rate of expansion (assuming it has not changed) to check when the explosion occurred - and obtain an answer of about 900 years; there is little doubt, therefore about the identification. Despite all that is known about the Crab it continues to pose some unusual problems.

Most other bright nebulae are clouds of gas which have been heated and ionized by the ultra violet light from a bright O or B type star in their midst: their temperatures are usually about 10000°K. In the case of the Crab, however, the observed light intensity can only be accounted for if the temperature were hundreds of thousands of degrees: this would require a fantastically bright central star, but the only one in the vicinity is certainly not rich enough in ultra violet: with the discovery of its strong radio emission - apart from the Sun it is a among the brightest radio sources in the sky - came further anomalies: its spectrum is relatively flat, resembling that from thermal sources but its intensity is much too great to be accounted for by a thermal origin. We saw in Chapter that Alfven and Herlofson were the first to propound the synchrotron process - the spiralling of very high speed electrons in a magnetic field - as a possible source of the emissions from radio stars. It was the U.S.S.R. theorist, Shklovsky, however who (in 1953) put forward the revolutionary idea that both the light and the radio waves from the Crab Nebula originate by the synchrotron process, as the only mechanism which can account for their intensity. This suggestion carried with it the prediction that both the optical and radio radiation should be polarized - because the electrons producing the radiation are accelerated in one preferred direction (in a plane at right angles to the magnetic field) instead of in random directions, as for the free-free transitions which result in ordinary thermal emission. Photographs of the Nebula were taken through polaroid set at different angles and within a year Russian and Dutch astronomers confirmed that the light from every part of the nebula is, in fact, plane polarized. ~~Brightness measure~~ Shklovsky also introduced a brightness measure as a means of estimating the distance of supernovae. This is based on his theoretical derivation of the surface brightness of an expanding shell which is radiating by the synchrotron mechanism. While this does not take account of all the factors involved distances obtained in this way are in reasonable agreement with those derived more directly, where this is feasible.

Radio astronomers set out to check whether the Crab's radio emission was also polarized - a much more difficult task because radio telescopes lack the fine resolution obtainable at optical wavelengths, and so tend to produce a smeared or averaged result for the area covered by their beam. Further, the rotation of the plane of polarization produced by the Faraday effect as the waves travel through ionized regions, tends to confuse the picture still further. However Vitkevitch in the U.S.S.R. could just detect the existence of plane polarization at 3 cm and this was confirmed shortly afterwards by Mayer McCullough and Sloanaker in the U.S.A. The direction and degree of the polarization agreed well with that found optically, so the reality of the synchrotron process as an important mechanism in the production of cosmic radio waves was thus firmly established. Estimates of the strength of the magnetic field yield a figure of 10^{-4} gauss, about ten times that which exists in interstellar space. The tracery of filaments which are so characteristic of the Crab Nebula cannot be the result of ionization by a hot star and it has been suggested that they may be related to large-scale electric currents circulating in the magnetic field. The origin of the high speed electrons responsible for the radiation is not yet known with certainty. Calculations indicate that they would lose most of their energy in producing optical emission in about 200 years, and since the nebula is over 900 years old a fresh source of cosmic rays must exist.

They may be left over from the original explosion, perhaps are still being supplied or may arise from nuclear reactions which occur when cosmic rays collide with atoms of the gas.

When American scientists began to use rocket-borne detectors to see whether there were any prominent sources of X-rays in the skies they were not surprised to find that one of several such sources was located in the Crab. Extremely energetic electrons are needed to make X-rays and their life would be unlikely to exceed one year, so the supply mhx must obviously be replenished. Astronomers are not yet decided whether xmm their source is associated with wisps of brightness which appear at intervals from the centre of Crab, or whether the cloud expelled at the time of the original explosion is still hot enough - 10^9°C or more - to provide them. It is scarcely a matter for surprise too that the Crab should be involved in yet another of the current x unresolved mysteries, that of the pulsating stars or pulsars. Late in 1968 American observers found one of them lying in the direction of the Crab - perhaps another side effect of the cataclysm that brought it into being - not only sending out regular radio pulses but simultaneous light flashes as well, the first pulsar to emit both visible and radio.

Other Supernova Remnants

The prominence of the Crab as a radio source prompted a search through historical records for other supernovae appearances, and for radio sources which possess characteristics similar to those of the Crab. There are only two recorded instances of supernovae since 1054: Tycho Brahe, the Danish astronomer who achieved fame as the first to make accurate observations of the position and movements of the planets, saw a bright supernova in 1572; and Johannes Kepler, who used Tycho Brahe's observations to show that the planets followed elliptical orbits, reported the second in 1604. Although neither had the use of a telescope their recording of the position of these bright stars was good enough to allow the remains of these explosions to be located: they are much less conspicuous than the Crab, appearing only as faint wisps of gas, but moving outwards: there is also an associated radio source in each case, which is weak but with non-thermal characteristics similar to the Crab.

A careful search of past records has yielded a number of instances of undoubted supernovae, of which the most outstanding is that of A.D. 1006, recorded from both Chinese and Arabian sources. At maximum it was so bright that objects could be seen by its light, which was compared to that at half-moon, so it probably outshone the Crab at its peak by 3 to 5 magnitudes. Recognition of a radio source associated with this supernova has not been easy since the method of recording positions used in oriental records (by their direction relative to nearby stars and to the location of the Moon) ~~to nearby stars and to the location~~ leads to uncertainties of up to 10°. Of two possible sources NGC 5882 and the Parkes source 1459-41, both of which are more than seventy times weaker than the Crab, the latter is more likely the remains of this explosion. Ancient Chinese records include also the following listings which from their descritpion are probably genuine supernova explosions.

Comment	Date	Position R.A.	 Dec.	Possible associated radio source
Discovered during day-time: visible to naked eye for 20 months	A.D.185	14^h	-60°	PKS 1439-62
A big yellow star which outshone all others	396	4^h	20°	None known
Visible during daylight	437	6^h40^m	20°	SL 34 : 1C 443
"As big as a peach"	902	1^h20^m	70°	CTA 1 : HB 3

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Two wellknown nebular objects, the Loop in Cygnus and 1C 443 whose origin was previously unknown were recognized as supernova remnants from the properties of the radio sources which are associated with them. Photographs taken at Palomar confirm a shell-like structure which is expanding. Altogether there are some 40 radio sources tentatively classified as remnants of supernova which have appeared in the Galaxy. The characteristics which indicate that a radio source is a supernova remnant are:-

(i) a non thermal radio spectrum
(ii) radio brightness distribution consistent with a shell structure
(iii) if it is visible optically it should show some filamentary structure
(iv) angular size large enough to exclude the possibility of its being an external galaxy
(v) location within 250 parsecs of the galactic plane (i.e. a population I member)

Details of those which are confirmed or are most probably supernova remnants are given in Table . One of the most interesting of these is Cassiopeia A.

Cassiopeia A

The most powerful radio source in the skies lies in the constellation Cassiopeia: it was discovered by the Cambridge group in 1948 in the course of observing the powerful source in Cygnus whose existence had been suspected by Hey and which Bolton had shown to be of small dimensions. The Cassiopeia source was too far north to be visible from Sydney. Despite its exceptional radio brilliance there appeared to be no optical object to account for it so F.G. Smith set up special equipment - using some old German radar aerials - to try to obtain an accurate position. The information he obtained was passed to Dewhirst of the Cambridge observatories, who was able to show that there was a very faint nebula close to the radio position. Photographs taken by Baade and Minkowski with the great Palomar 200" telescope confirmed this identification beyond any doubt: despite the faintness of the nebulosity which constitutes the still-expanding remains of a supernova, spectroscopic evidence showed that some of the filaments are moving at speeds around 5000 km/sec (200,000 miles per ~~mixxx~~ minute). They are moving so fast, in fact, that it is possible to see definite changes in their form on photographs taken only a few months apart. They are also very hot and highly ionized which combined with the turbulent motion provides the ideal conditions for the generation of radio waves.

The interpretation of this unusual radio source presented difficulties at first because, mixed up with these rapidly moving parts of the nebula, were other faint filaments which were almost stationary. As further photographs became available over a period of a few years the true picture became clear. The fast moving patches were indeed moving outwards, and from their speed the date of the original explosion from which they came was placed, within a few years, at A.D. 1702. There is no record of an unusually bright new star appearing at that time but this is scarcely surprising because although it appears to belong to the Type II or more powerful class of supernovae it is about 10,000 light years from us and at that distance it might not have reached 5th magnitude even at its peak. This would make it only just visible to the naked eye and certainly not a conspicuous object. The stationary patches of nebulosity mentioned above have a different spectrum from the exploding shell and are probably the result of collisions between the cold interstellar gas and the expanding filaments, as a result of which, they fall behind the main body of the expanding shell.

The next victim?

Heavy stars tend to have short and merry lives and are sure candidates for fireworks. We need have no fears about our Sun however, even though it is currently consuming its own hydrogen at the rate of 500 million tons a second: some thousands of millions of years hence it may swell in size and swallow up the inner planets but things will stay as they are for our lifetime and indeed for the next thousand million years at least. The life history of stars, though, is very dependent upon their mass: had our Sun retained as little as 25% more of the material from ~~which~~ which it condensed it would have already burned itself out - and this tale would not have been told.

Big stars exhaust their capital in quick time. With their greater gravity they become much hotter inside as they collapse, and more complicated nuclear reactions become possible than the simple hydrogen and helium burning which suffice for stars like the Sun. Successively heavier elements build up in the star's interior until so much iron is accumulated that cooling sets in, the trigger that detonates the series of events that culminate in the final fireball.

There has been no recorded supernova since Kepler's of 1604, which occurred just a few years before the introduction of the telescope. The next one will be of enormous interest to the astronomers, provided it doesn't go off in our immediate neighbourhood: perhaps it has already occurred in one of those quietly shining stars of the Milky Way, and the light and radio waves, with their tell-tale story of the catastrophe, are well on their way to us. In the meantime astronomers have to content themselves with watching for supernovae in other galaxies: their brilliance is so dazzling that they are easily recognizable at enormous distances on photographs taken with the world's greatest telescopes.

RADIO SOURCES ASSOCIATED WITH SUPERNOVA REMNANTS

Object	R.A. h m s	& Dec. ° '	Flux Intensity $(10^{-26} W m^{-2} (c/s)$	Frequency MHz	Spectral Index	Dimensions	Distance (parsec)	Comments
Tycho's Supernova	00 22.6	+63 52				6'	360?	Remnant of Type I supernova of A.D. 1572
Auriga A	04 57	+46 30				1.40	?	Remnant of Type II supernova
Crab Nebula	05 31.5	+21 59				3.5'x5.5'	1100	Remnant of Type I supernova of A.D. 1054
1C 443	06 14	+22 30	173	635	-0.45	50'	2000	Remnant of Type II supernova
Monoceros Nebula	06 35	+16 30	200	635	-0.35		1000?	
Puppis A	08 20.5	-42 50	183 90	635 2650	-0.5	55'		
Vela-X	08	-45	2360 1400	635 2650	-0.35 to -0.4	3.5°	500	Filamentary nebuloxity Stromlo 16. Complex of sources. Probably S/N remnant.
PKS 0902-38	09 02	-38 29			-0.4			Shell type structure, possibly S/N remnant
PKS 1209-52	12 09	-52 22	62 30	630 2650	-0.52			Shell type structure, possibly S/N remnant
PKS 1439-62	14 39	-62 15	20	2650	-0.5	52'		Filamentary nebulosity. Remnant of Supernova circa AD.185
PKS 1459-41	14 59	-41 54	1	2650	-0.6	diam 22'		Remnant of faint filamentary nebulosity S/N of AD.1006
PKS 1548-55	15 48	-55 59	115	2650	-0.3			Shell type structure, possibly S/N remnant.
Kepler's Supernova	17 27.7	-21 27	26 12	635 2650	-0.55	2.5'	1000	Remnant of Type I S/N of AD. 1604.
W28	17 57	-23	315 187	635 2650	-0.42	30'		Filamentary nebula; probably S/N remnant
3C 396.1	19 04	-03	25 9	635 2700	-0.4	60'		Probable S/N remnant
W49B	19 08	+09	(48) 25	635 2650	-0.33	5.4'x3.0'	14000?	Probable S/N remnant
CTB 72	19 20	+06	225 83	635 2700	-0.5	150'x100'		Probable S/N remnant
2C 1725	20 44	+50 20				2°x2.5°		
Cygnus Loop	20 49	+29 50				2.7	770	Remnant of Type II supernova
Cassiopeia A	23 21.2	+58 32			-0.77?	4'x4'	3400	Remnant of Type II supernova circa A.D. 1702
PKS 0525-66	05 25	-66 08					5500	