CHAPTER 8

INFLUENCE OF PULSARS ON SUPERNOVAE

In recent years there has been a great deal of effort to understand in detail the observed light curves of type II supernovae. In the standard approach, the observed light curve is to be understood in terms of an initial deposition of thermal energy by the blast wave; and a more gradual input of thermal energy due to radioactive decay of iron-peak elements is invoked to explain the behaviour at later times. The consensus is that the light curves produced by these models are in satisfactory agreement with those observed.

In this chapter we discuss the characteristics of the expected light curve, if in addition to the abovementioned sources of energy, there is a continued energy input from an active central pulsar. We argue that in those rare cases when the energy loss rate of the pulsar is comparable to the luminosity of the supernova near light maximum, the light curve will be characterized by an extended plateau phase. The essential reason for this is that the pulsar luminosity is expected to decline over timescales which are much longer than the timescale of, say, radioactive decay. The light curve of the recent supernova in the Large Magellanic Cloud is suggestive of continued energy input from an active pulsar. A detection of strong UV, X-ray and γ-ray plerion after the ejecta becomes optically thin will be a clear evidence of the pulsar having powered the light curve.

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8.1 INTRODUCTION

In the previous chapters we have discussed the effect of pulsars on the morphology and evolution of supernova remnants. We have also discussed (in chapter 4) the possible effect of a rapidly spinning neutron star on the supernova explosion itself. Whatever be the mechanism responsible for the explosion, if one accepts the hypothesis that a neutron star is born in every type II supernova, and that the majority of them will function as pulsars, then it is natural to ask whether the energy radiated by the pulsar will have any consequence on the observed properties of the supernova, for example, the light curve. We wish to make some remarks on this interesting question in this chapter.

The rotational energy released by a pulsar can, in principle, affect the surrounding supernova envelope in two ways.

A. It may accelerate it and/or

B. It may heat up the ejecta and modify the light curve.

Since the kinetic energy of the expanding envelope is typically 10^{51} ergs, the pulsar is likely to have a significant dynamical effect only if it is an ultrafast pulsar, as we shall see in the next section.

The typical luminosity of a supernova is $\sim 10^{42}$ erg s^{-1} for the first ~ 100 days. Thus, unless the luminosity of the pulsar is comparable to this it cannot be responsible for the observed radiation. Assuming a standard magnetic field $\sim 10^{12}$ gauss, this would imply a spin period $\lesssim 10$ milliseconds. To recall our main conclusion from chapters 2 and 3, such fast pulsars must be very rare. But in those rare cases one does expect the energy input from the pulsar to modify the predictions of the standard models of supernova light curves.

The next section summarizes the previous work on the influence of pulsars on supernovae. In section 8.3 we present a slightly modified picture of how the energy released by the pulsar can influence the thermal energy of the supernova envelope. We also summarize the clear signatures of a supernova with an active pulsar at the centre. The recent supernova SN 1987A in the Large Magellanic Cloud is particularly interesting because of its very odd light curve. In section 8.4 we speculate on the possibility that a central pulsar may, in fact, be responsible for the observed light curve of this supernova.

8.2 EARLIER WORK

The first paper to discuss the influence of pulsars on supernova light curves was by Rees (1970). In his approach, the supernova explosion was attributed to the initial shock accompanied by the formation of a neutron star. He argued that if the central pulsar was a millisecond pulsar, then its pulsed luminosity (in the W and X-rays) would be sufficient to explain the plateau phase of a type II supernova; since during this phase the envelope is opaque, this energy will be absorbed by it and reradiated in the visible.

Gaffet (1977) has explored a variant of the above model suggested by Rees, in which the energy input from the pulsar is in the form of low-frequency magnetic dipole radiation, rather than high frequency pulsed emission. The light curve predicted by this model, although in agreement with the observed light curves during the initial phase, is not consistent with the late time behaviour.

Ostriker and Gunn (1971) and later Bodenheimer and Ostriker (1974) used the pressure of the magnetic dipole radiation from the pulsar to produce the explosion itself, and also to heat up the envelope. In order to do this, they invoked a very high luminosity pulsar, $L \sim 10^{44}$ erg s^{-1}. Although this is a very attractive model, two of its predictions are inconsistent with observations:

1. Even with such a high pulsar luminosity, the shock takes a long time to develop and consequently the light curve evolves very slowly, the maximum being reached $\sim$ 100 days after the formation of the pulsar.

2. For a considerable length of time after this, the luminosity of the supernova will be equal to the spindown luminosity of the central pulsar. Thus the predicted luminosity during the plateau phase is two orders of magnitude more than what is observed in typical supernovae.

But an interesting feature of the light curve predicted by this model is that the duration of the plateau phase will be much longer than that expected from the standard models.

8.3 AN ALTERNATIVE SUGGESTION

In this section, we shall elaborate on a slightly different scenario than the one explored by Rees (1970). One knows that even in the case of the Crab pulsar, the energy carried away by the high-frequency pulsed radiation is only a small fraction of the total rotational energy lost by the pulsar. In the model of the pulsar suggested by Goldreich and Julian (1969), the rotational energy lost goes into accelerating a relativistic wind with a frozen-in magnetic field. The energy in the pulsed radiation is what these particles radiate within the speed-of-light cylinder of the pulsar. The cavity surrounding the pulsar is thus filled with this relativistic plasma and magnetic field. One therefore expects these particles to emit synchrotron radiation. Or, in other words, there will be a "mini plerion" surrounding the pulsar. As has been argued by Pacini and Salvati (1973), in this early phase the **total luminosity of the plerion will be comparable to the spindown luminosity of the pulsar.** Also, as in the case of the Crab nebula, one expects most of this energy to be radiated as X-rays and γ-rays.

When the ejecta is thick for Compton scattering, most of the very high energy photons will be degraded to X-ray energies in the envelope, thus depositing a fraction of their energy. Once the energy of these photons fall below ~ 100 KeV, they will be absorbed due to photoelectric process. Thus most of the energy of these high energy photons will go into heating the ejecta. This is in addition to the heating due to the pulsed high-frequency radiation from the pulsar as envisaged by Rees (1970). This way almost the .entire rotational energy released by the pulsar can be used to heat the envelope. The hot envelope will have a temperature $\sim 10^4$ K, and will radiate primarily in the optical region. In a steady state, the bolometric luminosity of the envelope will roughly equal the pulsar output. This will continue as long as the Compton scattering optical depth of the envelope is much larger than unity (these effects have been discussed in detail in a recent paper by McCray et.al. (1987)).

Predictions Of This Model

Some clear predictions follow from this scenario in which an active central pulsar is the main source of energy for the observed light curve, particularly at late times.

(1) One expects the plateau phase of the light curve to be rather prolonged. As long as the optical depth of the ejecta is sufficiently high, the luminosity of the supernova will be roughly equal to the luminosity of the pulsar, and hence it will remain essentially constant. This is to be expected since the luminosity of the pulsar will decline appreciably only over its initial spindown timescale, which is expected to be much longer than the timescales for the plateau phase predicted in the standard model (e.g. Weaver and Woosley 1980).

(2) As the envelope of the supernova expands, it will eventually become optically thin and more and more high energy photons will escape without being reprocessed. At this stage the luminosity of the supernova envelope will begin to drop rapidly. This decline in optical emission will be accompanied by a rise in the luminosity at higher frequencies, since the radiation from the pulsar bubble would be directly observable. An important characteristic of this high energy continuum will be its high degree of linear polarization. When the photoelectric processes also becomes less important, polarised W continuum will emerge.

(3) **The pulsar bubble will also be a source of intense radio emission.** But free-free absorption in the ejecta is likely to hide this radio emission for more than a decade.

As was mentioned in the previous chapter, non-thermal radio emission has been detected from several supernovae within a few 'months after the outburst. One of the suggestions that has been made to explain this (Pacini and Salvati 1981) is that the observed radio radiation is from a mini-plerion; very early fragmentation of the ejecta is a prerequisite for this model. The pros and cons of this model were also discussed in the previous chapter. Here we wish to make one further remark. If the ejecta has in fact fragmented into filaments, then one should also be able to see the polarized non-thermal W, X-ray, and γ-ray continuum. But this is not expected in the alternative model suggested by Chevalier (1982a).

8.4 THE RECENT SUPERNOVA IN THE LARGE MAGELLANIC CLOUD

This long-awaited naked eye supernova (SN 1987A) is remarkable in many respects, notably in its light curve. In figure 8.1 we have compared the blue band light curve of SN 1987A (upto the time of writing) with that of a typical SNII-P. The significant points of difference to be noted are

1. SN 1987A is quite subluminous. Its peak. brightness is an order of magnitude less than that of a standard SNII.

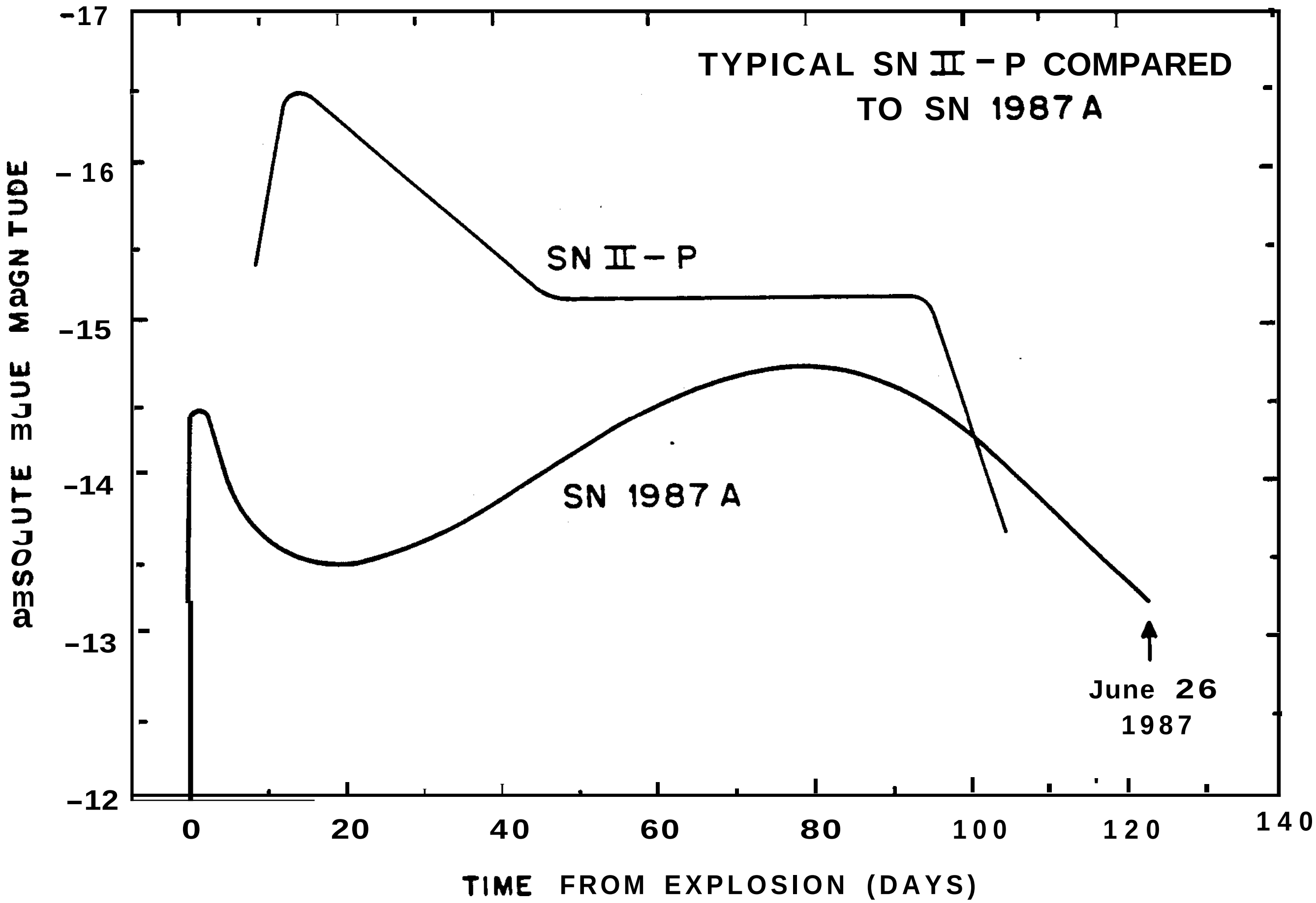

Fig. 8.1: A comparison of the blue band light curve of SN1987A with that of a standard type II (plateau) supernova. Data for SN1987A from Menzies et. al. (1987) and IAU Circular nos. 4369, 4370, 4374, 4387, 4388, 4391, 4405 and 4411. A distance modulus of 18.5 and Av = 0.6 for SN1987A has been assumed. The standard SNII-P light curve has been adapted from Barbon et. al. (1979).

2. In a standard SNII, the maximum luminosity is reached ~ 15 days after the explosion, and begins to fade rapidly after ~ 60-90 days. In contrast, in the case of SN 1987A the maximum luminosity was reached as late as ~ 90 days after the explosion. Further, although its luminosity has started declining, there are indications that the rate of decline has decreased substantially (IAU circular no. 4412).

Since such a "flat-topped" light curve is precisely what one expects in the scenario being discussed in this chapter, it is tempting to speculate whether SN 1987A is being powered by a central pulsar.

One of the things one can say with reasonable confidence is that even if there is an active pulsar, the pressure of the pulsar radiation could not have been responsible for this supernova explosion. Because of the detection of neutrinos from the gravitational collapse one knows that the ejecta acquired a kinetic energy $\sim 10^{51}$ ergs within a couple of days, if not within a few hours, after the formation of a compact object. Only a pulsar with a period ~ 1 ms and an implausibly large magnetic field $> 10^{14}$ gauss will be able to release $\sim 10^{51}$ ergs within a couple of days. If indeed there were such a pulsar at the center then the luminosity of the supernova should have been at least a thousand times more than that observed.

Let us next turn to the light curve and ask whether it is consistent with what one expects if there is a strong central pulsar. Indeed, as we shall now argue, without a continuing source of energy input into the envelope it is very difficult to explain the observed light curve. It is now fairly certain that the progenitor of this supernova was the blue supergiant star Sanduleak 202-69^{o}. Its presupernova size must have been $\sim 2 \times 10^{12}$ cm. Expansion from such a small initial size would result in a severe adiabatic loss of the initial thermal energy deposited by the shock wave. The high expansion velocity seen in SN 1987A, and its subluminous nature, are consistent with this. As most of the initial energy is thus lost to expansion, the observed optical luminosity of the supernova could only have been maintained if there was a continued input of thermal energy into the envelope.

Woosley et.al. (1987) have suggested that the late time energy input could be due to radioactive decay of unstable nuclei synthesized in the explosion. In our opinion, a central pulsar would naturally account for this energy injection. This would require a pulsar with a spin period ~ 5 ms with a standard magnetic field $\sim 5 \times 10^{12}$ gauss (corresponding to the observed luminosity $\sim 10^{42}$ erg s^{-1}). Given such a pulsar, it is interesting to ask how long after the explosion the effect of the pulsar will be noticeable. This will happen at a time t_1 when the total amount of thermal energy deposited by the pulsar equals the thermal energy content of the envelope. due to initial shock heating. As remarked above, even though the shock deposits $\sim 10^{51}$ ergs, much of it is lost in adiabatic expansion. Thus

$$L_{PSR} \cdot t_1 = E(t_1) = E_{initial} \left(R_{initial} / v t_1 \right)$$

where L_{PSR} is the pulsar's **spindown** luminosity, $R_{initial}$ the radius of the progenitor and v the expansion velocity. From this one obtains

$$t_1 \sim 12 E_{51}^{1/2} R_{12}^{1/2} L_{42}^{-1/2} v_4^{-1/2} \textbf{ days}$$

where $R_{12} = R_{initial}/10^{12}$ cm ; $E_{51} = E_{initial}/10^{51}$ erg; $v_4 = v/10^4$ kms^{-1} ; $L_{42} = L_{PSR}/10^{42}$erg s^{-1}. From this time onwards the light curve will be determined by the pulsar input. The fact that the supernova started brightening two weeks after the outburst is consistent with this picture. A detailed explanation of the spectral evolution will obviously require sophisticated calculations of the radiation dynamics in the envelope. On the other hand, as was mentioned in the previous section, this model makes some definite predictions that can be verified by future observations.

(1) The optical luminosity of the supernova should stay roughly constant till the envelope becomes optically thin to Compton scattering. McCray et.al. (1987) estimate this time to be $t_2 \sim 2.5\, \zeta^{1/16} M_{ej}^{1/2} v_4^{-1}$ months. where M_{ej} is the ejected mass in solar masses and ζ is the metallicity of the ejecta.

(2) When the optical luminosity begins to decline steadily, the spectrum of the supernova should become progressively harder. The UV and X-radiation should easily be detectable with the existing facilities.

(3) The radio radiation may be obscured for several years unless the ejecta breaks up into filaments. A flux of ~ 1000 Jy at 1 GHz may be expected if the ejecta becomes optically thin within ~ 10 years.

If the above predictions are not borne out by future observations then it would argue against the suggestion made here, namely that a central pulsar is an important source of energy input at present.

8.5 SUMMARY

As has been mentioned several times in previous chapters, pulsars are believed to be born in type II supernova explosions. We have argued in this chapter that if these pulsars are fast rotators, and are also endowed with strong magnetic fields, they can significantly influence the light curves of supernovae. It is therefore surprising that standard models, which do not invoke the central pulsars, are able to predict light curves which are in reasonable agreemnet with observations. In our opinion, this is again trying to tell us that the majority of pulsars do not have very high spindown luminosities even immediately after their birth. But in rare cases the initial luminosity of the pulsar could be quite high, and the light curves of supernovae will have the peculiarities discussed in detail in this chapter. It is therefore worth paying particular attention to those supernovae the light curves of which do not fit into the standard models; for these may be the ones harbouring fast pulsars.

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