CHAPTER 4

MAGNETIC TORQUES AND THE ORIGIN OF SLOW PULSARS

In the previous chapters it was argued that the majority of young pulsars may be relatively slow rotators. Some possible reasons for this are discussed in this chapter. It is conceivable that the newly born neutron star may, in fact, have rather high angular momentum, but that it is quickly extracted due to the magnetic coupling with the surrounding envelope of the progenitor star before it is ejected in a supernova explosion. The effectiveness of this mechanism is discussed in some detail. If this is the reason for the slow rotation of pulsars, then it is interesting that the amount of rotational energy extracted from the neutron star is sufficient to be responsible for the supernova explosion itself.

CONTENTS

CHAPTER 4

MAGNETIC TORQUES AND THE ORIGIN OF SLOW PULSARS

CHAPTER 4

MAGNETIC TORQUES AND THE ORIGIN OF SLOW PULSARS

4.1 INTRODUCTION

The important conclusion arrived at in chapters 2 and 3 is that the majority of pulsars are born spinning slowly. This is contrary to conventional thinking which would suggest that pulsars must be born spinning rather rapidly. In this chapter we would like to speculate on possible reasons for the slow rotation of such young neutron stars. The main objective is to point out some possible scenarios rather than to do detailed calculations to justify them. We shall be drawing mainly from ideas and scenarios that already exist in the literature, although advanced in very different contexts. We feel that it would be worthwhile to speculate on some possible connections.

It is believed that a neutron star is born in the gravitational collapse of the core of a normal star at the end of its nuclear evolution; and this is accompanied by a supernova explosion. The resulting rotation speed of the neutron star would then be decided by

(a) the angular momentum of the core prior to collapse and

(b) any process that can transport angular momentum away from the core.

The average spin rates of main sequence stars lie in the range $\Omega \sim 10^{-5}-10^{-4}\ s^{-1}$ for different spectral types (McNally 1965). If the core has an angular velocity similar to the angular velocity at the stellar surface, then after collapse, a slow pulsar would be a natural product. Fricke and Kippenhahn (1972) have argued that even if the core is rotationally coupled to the envelope only upto the Helium burning phase, and thereafter evolves conserving its own angular momentum, the angular velocity of the resulting neutron star after core collapse will only be $\sim 10\ s^{-1}$.

However, it is usually believed that stars are in a state of differential rotation, and spin rate of the core may exceed the spin rate observed at the surface by an order of magnitude (Bodenheimer and Ostriker 1973). Observational data is not clear in this respect. The most extensive observations are, of course, those made on the Sun. While there are indications that the solar core may be rotating faster than the rest of the sun (Howard, 1984; Deubner and Gough, 1984), the results are not unambiguous and it is very difficult to draw any quantitative conclusions.

In view of these uncertainties regarding the angular momentum of the presupernova star we shall discuss three different cases in this chapter.

In section 4.2 we shall discuss possible braking of the core of the neutron star progenitors prior to collapse. In section 4.3 we shall discuss the case where the pre-collapse core has a large angular momentum. In this case, to form a slowly rotating neutron star (or to form a neutron star at all) processes of angular momentum removal must be considered. Section 4.3.1 describes the case where the angular momentum of the core is so large that collapse is halted due to rotation before neutron star density can be reached. In section 4.3.2 we discuss moderately rotating cores, for which collapse occurs without being interrupted by rotation, but the resulting neutron star is a rapid rotator just after birth.

The most plausible mechanism for angular momentum removal appears to be a magnetic coupling of the core with the surrounding envelope. If there is a differential rotation between the core and the envelope, the magnetic lines of force are twisted, thus exerting a torque which results in angular momentum transfer from the core to the envelope. In this chapter, this is the only process we shall consider for angular momentum transport.

4.2 MAGNETIC BRAKING OF STELLAR CORES

As was mentioned before, it has been suggested by Fricke and Kippenhahn (1972) that a pre-collapse stellar core may have very little angular momentum. This state of affairs is possible even if the core were originally differentially rotating, but the angular momentum was extracted due to magnetic coupling with the envelope.

The tensile strength of magnetic field lines is of order

$$F \sim B^2 R^2 \qquad (4.1)$$

where B is the magnetic field and R the typical dimension of the system. The core of density ρ, size R and angular velocity Ω has an angular momentum

$$L \sim \rho R^3 . R^2 . \Omega \sim \rho R^5 \Omega . \qquad (4.2)$$

Twisting of the field lines will generate a torque

$$N \sim F.R \sim B^2 R^3 . \qquad (4.3)$$

This torque will remove angular momentum from the core in a timescale (Bisnovatyi-Kogan 1971):

$$t_m \sim \frac{L}{N} \sim \frac{\rho R^2 \Omega}{B^2} \qquad (4.4)$$

in terms of typical core parameters,

$$t_m \sim 3.10^4 \rho_6 R_9^2 B_6^{-2} \Omega \quad yr$$

where $10^6 \rho_6$ gm cm^{-3} is the density, $10^9 R_9$ cm the core radius and $10^6 B_6$ Gauss the magnetic field. In choosing these units we have in mind the Carbon burning phase. We have singled out this phase because Ruderman and Sutherland (1973) have suggested that the magnetic flux of the neutron star is generated during this phase - during the collapse it is this field that gets amplified. The density of this core will be approximately 10^6 gm/cc (see e.g. Sugimoto and Nomoto 1980; Trimble 1982 and references therein), and the corresponding radius $\sim 10^9$ cm. If, as was mentioned above, the magnetic fields of neutron stars is the amplified "fossil" field generated in this phase, then the magnetic field of the core will be $\sim 10^6$ gauss.

Let us now estimate this timescale t_m for magnetic braking for two illustrative values of the angular velocity of the core.

Case I: $\Omega_{CORE} = \Omega_{MAX}$

This maximum value of angular velocity is equal to $\sqrt{\pi G \rho}$. Using 10^6 gm/cc for the average density of the core, we find

$$\Omega_{MAX} \sim 0.4\ s^{-1}. \tag{4.5}$$

For this case,

$$t_m \sim 10^4\ yr. \tag{4.6}$$

It is interesting to note that this is much larger than the duration of the Carbon burning phase which is believed to last for a few hundred years (it might be recalled that the pre-supernova lifetime of the star beyond this phase is only a few tens of years). Therefore if the core were spinning maximally, there may not be enough time for the magnetic torque to slow it down. In this case one would expect a very fast neutron star to be born. It should be remarked that if there is significant magnetic torque prior to the Carbon burning phase, for example, during the Helium burning phase, then the core would not have been spinning very rapidly to begin with. Further slowing down during the Carbon burning phase would then result in a slow pulsar. This is illustrated below.

Case II: $\Omega_{CORE} \sim 10\,\Omega_{SURFACE}$

Let us suppose, for example, that the core is rotating only 10 times faster than the surface layers, and that the period of the latter is $\sim$ a day. Under these conditions,

$$t_m \lesssim 30 \text{ yr.} \tag{4.8}$$

Clearly one is not able to say much at this stage about the angular momentum of the core just before it collapses. But if the neutron star is endowed with a magnetic field at birth, then it is tempting to speculate that there might be a correlation between the strength of the magnetic field and the period of rotation: longer periods at birth being associated with higher fields (Srinivasan 1985b). A recent analysis of pulsar data by Narayan (1987) seems to show such a correlation.

In the remaining sections of this chapter we shall assume that just prior to collapse the core had rather high angular momentum and draw some conclusions about its implications for the events immediately following the birth of the neutron star.

4.3 RAPIDLY ROTATING CORES

4.3.1 Ultra Rapid Cores

If the angular momentum of the core exceeds a certain critical value, then the rotation will prevent a collapse. Unless angular momentum is extracted all the while, the collapse to nuclear densities cannot occur.

During a collapse that conserves angular momentum the ratio of rotational energy to gravitational energy increases:

If R is the size of the core, M its mass, and L_0 is the angular momentum, then

the rotational energy, $E_{rot} \sim L_0^2/MR^2$, and

the gravitational energy, $E_{grav} \sim GM^2/R$.

Therefore the ratio $\beta \left(\equiv \frac{E_{rot}}{E_{grav}} \quad \frac{L_0^2}{GM^3}\cdot\frac{1}{R}\right)$ increases as R decreases. If L_0 is sufficiently large, during the collapse E_{rot} and E_{grav} may become approximately equal before nuclear density is reached, and at that point the collapse will stop[6]. Further collapse, will only be possible if angular momentum is removed from this stalled configuration. But this

---

a. Exactly at what value of β the collapse stops depends to some extent on the equation of state, especially if adiabatic index is very close to 4/3 (see, for example, Tohline 1984).

is possible if there is efficient magnetic coupling between the core and the envelope. The timescale for this process can be estimated from (4.4). Using the limiting value for the angular velocity $\Omega = \Omega_{max} = (\pi G \rho)^{1/2}$, one obtains (for a core mass $\sim 1 M_\odot$)

$$t_m \sim 20 \text{yr}\ \rho_8^{5/6}\ B_8^{-2} \qquad (4.9)$$

where $10^8 \rho_8$ gm cm^{-3} is the density and $10^8 B_8$ Gauss is the magnetic field of the core at the stage where collapse is halted. The above timescale t_m is also now the collapse timescale, since collapse cannot proceed unless angular momentum is' continually removed. If magnetic flux is conserved during the collapse, then

$$B\rho^{-2/3} = \text{constant}.$$

For a neutron star field of 10^{12} Gauss, and density of 10^{14} gm/cm^3,

$$B\rho^{-2/3} = 4.6\times10^2 \text{ Gauss cm}^2 \text{ gm}^{-2/3}.$$

Hence B_8 can be obtained from

$$B_8 \rho_8^{-2/3} = \left(\frac{B\rho^{-2/3}}{4.6\times10^2 \text{ Gauss cm}^2 \text{gm}^{-2/3}}\right). \qquad (4.10)$$

Eq.(4.9) may then be rewritten using (4.10) as

$$t_{collapse} \sim t_m \sim 20 \text{yr}\ \rho_8^{-1/2} \left(\frac{B\rho^{-2/3}}{4.6\times10^2 \text{ Gauss cm}^2 \text{gm}^{-2/3}}\right). \qquad (4.11)$$

Thus, for a given magnetic flux, the collapse timescale will be longer if the collapse has been halted at a lower density. The dependence of the collapse timescale on the magnetic field is rather strong. A range of (1-30) x 10^{12} Gauss in the final neutron star field will correspond to a range 20 years - 8 days in collapse timescale.[6]

Pacini (1983) has exploited this strong dependence of collapse timescale on magnetic field to explain the occurrence of millisecond pulsars in binary systems with nearly circular orbit.

As is clear from the above discussion, the collapse of the ultra-rapid core goes through two phases. In the first, rotation is unimportant and collapse occurs in a dynamical timescale. This phase ends. when rotation arrests the collapse. In the second phase collapse occurs only by removal of angular momentum and proceeds on the magnetic timescale 4.11. Since this timescale is never smaller than the free fall timescale, all successive configurations in this slow collapse phase will have equilibrium between rotation and gravity, that is, they will be spinning at their limiting angular velocity. Finally when the neutron star is formed, it will have a spin period of about a millisecond. The amount of rotational energy extracted in this collapse process will be

$$\Delta E_{rot} = - \int_{J_i}^{J_f} \frac{\partial E_{rot}}{\partial J} \, dJ$$

---

6 Generation of toroidal magnetic field by winding up the initial field structure may give a much smaller timescale, as discussed in the next section. This, however, does not change the qualitative picture under discussion here.

where J is the angular momentum and E_{rot} is the rotational energy of the configuration with angular momentum J.

If I is the moment of inertia and Ω is the angular velocity, then

$$J = I\Omega \qquad \text{and} \qquad E_{rot} = \frac{1}{2} I\Omega^2 = \frac{J^2}{2I} .$$

$$\therefore \quad \frac{\partial E_{rot}}{\partial J} = \frac{J}{I} = \Omega .$$

Since all the configurations are rotating at limiting angular velocity

$$\Omega \sim (\pi G\rho)^{1/2} \sim (\pi G M)^{1/2} R^{-3/2}$$

and $I \sim MR^2$, the angular momentum

$$J \sim MR^{1/2} (\pi G M)^{1/2} , \text{ giving } \quad R \sim J^2/\pi G M^3 .$$

Hence

$$\frac{\partial E_{rot}}{\partial J} = \Omega(J) = \frac{\pi^2 G^2 M^5}{J^3}$$

$$\text{and} \quad \Delta E_{rot} \sim \frac{\pi}{2} G M^2 . \pi G M^3 . \left[\frac{1}{J_f^2} - \frac{1}{J_i^2}\right] = \frac{\pi}{2} G M^2 \left[\frac{1}{R_f} - \frac{1}{R_i}\right],$$

roughly equal to the gravitational energy released in the collapse process. If $R_f \ll R_i$, then ΔE_{rot} is almost equal to the gravitational binding energy of the final configuration. The collapse to a neutron star will thus release a rotational energy $\sim 10^{53}$ erg.

This energy must be deposited in the stellar envelope. The envelope has a gravitational binding energy of $\sim 10^{51}$ erg, and therefore cannot store this amount in internal energy without getting disrupted. For the envelope to still remain intact, this energy must then be radiated away. A lower limit to the rate of release of rotational energy can be obtained by dividing the rotational energy of initial configuration by the corresponding collapse timescale.

$$-\frac{dE}{dt} \gtrsim \frac{E_{rot}}{t_m} \sim \frac{E_{grav}}{t_m} \sim 10^{42} \rho_8^{5/6} \left(B_{12}^f\right)^2 \text{ erg s}^{-1} \qquad (4.12)$$

where $10^{12} B_{12}^f$ gauss is the final value of the magnetic field when the configuration reaches nuclear density. A core mass of $\sim 1M_\odot$ has been assumed. This rate of loss of rotational energy is far in excess of the Eddington Luminosity

$$L_{Edd} \sim 10^{38} \left(M/M_\odot\right) \text{ erg s}^{-1} \qquad (4.13)$$

which the star can stably radiate in photons. The only way for the envelope to remain stable is by radiating away this energy in the form of neutrinos and by expanding somewhat to accommodate the deposited angular momentum. However, it is most likely that much of this released energy (4.12) will be converted into kinetic energy of the stellar envelope which will expand and move away from the collapsing core. Though the amount of energy released is substantial, the rate (4.12) is not sufficient to produce a standard supernova explosion. Nevertheless, one would expect the envelope to be gradually accelerated and expelled over the collapse timescale (4.11). Therefore, when the neutron star is finally formed, there will hardly be any matter left around it to which it can couple magnetically and slow down further. All these objects will then be functioning as pulsars with periods $\sim$ a millisecond.

It is also possible that the coupling with the surrounding matter weakens even before the neutron star is formed. In this case one will be left with a fast-spinning intermediate density object which has been named a "fizzler" in the literature (see, for example, Shapiro and Lightman 1975; Tohline 1984). No known examples of such objects, however, exist. Once the near-zone magnetic coupling is no longer effective, the fizzler has to wait much longer to collapse and form a neutron star. Since it is magnetized, it will emit magnetic dipole radiation, which gives a spindown torque

$$N \sim \frac{B^2 R^6 \Omega^3}{c^3} \tag{4.14}$$

and, therefore, a timescale for removal of angular momentum

$$t_m \sim \frac{c^3 \rho}{R \Omega^2 B^2} . \tag{4.15}$$

For $\sim 1 M_{\odot}$ object spinning at minimum period, and with a magnetic flux equal to that for a $10^{12} B_{12}^f$ Gauss neutron star,

$$t_m \sim 3.10^6 \rho_8^{-1} (B_{12}^f)^{-2} \; yr . \tag{4.16}$$

Collapse to neutron star densities will, therefore, take several million years. If, on the other hand, ohmic decay substantially reduces the magnetic field over this period, then the collapse timescale will lengthen and neutron star density may never be reached. However, if the collapse is halted at near neutron star density ($\rho \gtrsim 10^{13}$ gm cm^{-3}), then such a fast spinning object is likely to lose angular momentum very rapidly by Gravitational radiation, and a stable neutron star will form in a timescale of order a few seconds to a few days (Shapiro and Lightman 1975).

Irrespective of the way the collapsing core sheds its angular momentum, all neutron stars formed from the ultra rapid cores will be spinning very fast. Our result that most pulsars are born slow would then indicate that not many neutron stars are formed this way.

4.3.2 Cores With Moderate Angular Speeds

In this case collapse will proceed to nuclear density in a free fall timescale of a few milliseconds, unhindered by rotation. The neutron star that is formed will be spinning fast - with a rotation period of a few milliseconds and will be surrounded by the rest of the stellar matter very much like in the case of a non-rotating collapse.

Let us now investigate the role of the magnetic field during and after the collapse. The magnetic energy increases in constant proportion with the gravitational binding energy if the magnetic flux $\Phi_0 = BR^2$ is conserved:

$$E_{mag} \sim B^2 R^3 \sim \Phi_0^2 R^{-1};$$
$$E_{grav} \sim G M^2 R^{-1}$$

$$\therefore \quad \alpha \equiv \frac{E_{mag}}{E_{grav}} \sim \Phi_0^2 / G M^2 = \text{constant.} \qquad (4.17)$$

In a typical neutron star this ratio of magnetic energy to gravitational energy is

$$\alpha \sim 10^{-12} B_{12}^2 \qquad (4.18)$$

where $10^{12} B_{12}$ gauss is the final value of the magnetic field. Since the value of α remains the same during the collapse, it is evident that magnetic field will be of hardly any importance. This has also been confirmed by detailed numerical calculations of Symbalisty (1984) and LeBlanc and Wilson (1970).

The magnetic field may be a silent spectator during the collapse process, but as pointed out first by Kardashev (1965) and later by Bisnovatyi-Kogan (1971) and Kundt (1976) it may assume major importance after the collapse. Due to the large electrical conductivity of the stellar matter the magnetic field will be anchored to the matter surrounding the neutron star. In a state of strong differential rotation between the neutron star and the envelope, large shearing of the original field structure will build up toroidal fields. The energy in this toroidal field comes at the expense of the rotational energy of the neutron star. In other words, the toroidal field thus produced exerts a torque on the neutron star to slow it down. The strength of the toroidal field generated after n cycles of differential rotation is $B_t \sim B_0 n$, where B_0 is the initial field. The magnetic energy grows as

$$B_t^2 R^3 \sim B_0^2 n^2 R^3 \sim B_0^2 \Omega^2 t^2 R^3$$

where Ω is the angular speed of differential rotation. Since the initial magnetic energy

$$E_{mag}^0 \sim B_0^2 R^3 = \alpha E_{grav} ,$$

the magnetic energy after a time t can be expressed as

$$E_{mag} \sim E_{mag}^0 \Omega^2 t^2 . \tag{4.19}$$

This energy will become comparable to the rotational energy in a timescale

$$\tau \sim \left(\frac{E_{rot}}{E_{mag}^0} \right)^{1/2} \Omega^{-1} . \tag{4.20}$$

This is the basic **timescale** involved in the process. In the particular case when the angular speed is near the limiting speed,

$$\tau \sim \frac{1}{\Omega \sqrt{\alpha}} \tag{4.21}$$

since in this case $E_{rot} \sim E_{grav}$.

For a neutron star the limiting angular velocity is $\sim 10^4 \ s^{-1}$, and therefore

$$\tau \sim 10^2 \sec \sqrt{\frac{10^{-12}}{\alpha}} \sim \frac{10^2}{B_{12}} \sec. \qquad (4.22)$$

For $B_{12} \sim 1$ to 30, τ ranges from ~ 100 to ~ 3 seconds. This, then, is the timescale in which the stored rotational energy ($\sim 10^{53}$ erg) can be converted into the magnetic energy of the toroidal field. Bisnovatyi-Kogan (1971) and Kundt (1976) have suggested that this conversion may be responsible for the observed supernova outbursts.

This is an interesting suggestion particularly since attempts to produce supernova explosions in numerical experiments without the inclusion of rotation and magnetic field have so far met with only limited success, if any. The standard scenario for a type II supernova explosion has been the hydrodynamic shock resulting from "core bounce" (Woosley and Weaver 1986). As the collapsing core reaches the nuclear density the collapse is halted, but the kinetic energy of infall allows overcompression of the core beyond the equilibrium size. Finally a "bounce" from the overcompressed state sends a shock wave through the surrounding matter. It has been a long-standing hope that this shock wave would result in a supernova explosion. Extensive computations have been made during the last two decades to follow the development of this shock, but the hope of producing a standard supernova explosion has not been realized. Burrows and Lattimer (1985) have argued that it is unlikely that further improvement of the equation of state for nuclear matter, or of the numerical codes employed, will help to produce a "prompt" explosion. Bethe and Wilson (1985) have proposed a "delayed" mechanism, in which the original bounce shock, after it has stalled and matter is falling through it, is revived by means of neutrino heating. Though they were able to obtain an explosion this way, the energy of the outburst was about an order of magnitude less than what is observed and in any case other workers have not been able to reproduce this result.

In view of the above difficulties with the standard model one should perhaps take seriously the role of rotation and magnetic fields. It is conceivable that the bounce shock mechanism, aided by the toroidal field will be able to produce the explosion. This is an attractive combination particularly in view of the fact that many of the magnetorotational supernova models assume artificial geometries and perhaps unreasonable initial conditions. For example, the calculations of Bisnovatyi-Kogan et.al. (1976) and Ardelyan et.al. (1979) assume that the envelope has no infall velocity. But given this, they are able to produce the explosion by tapping the stored rotational energy. This is where invoking the stalled bounce shock may prove useful. In fact such an attempt to combine the two mechanisms was made by Muller and Hillebrandt (1979). With a combination of a near-successful bounce shock and the energy in the wound up magnetic field they were able to obtain a supernova explosion.

As mentioned above, the results of all these calculations should be viewed with some caution owing to the various simplifying assumptions made. It is nevertheless intuitively suggestive that the stored rotational energy can not only play a part in the supernova explosion, but may in fact be essential. If so, this will provide a natural explanation for the relatively small angular momentum of newly born pulsars.

4.4 SUMMARY

In the previous two chapters we presented detailed arguments which suggest that newly born pulsars may be rotating much slower than generally believed. In this chapter we have explored some possible reasons for why this may be so. The main conclusions can be summarized as follows:

1. It may simply be that the pre-supernova core did not have much angular momentum. Various mechanisms, in particular, the magnetic coupling between the core and the mantle might have slowed down the core. But this is unlikely to have happened if the magnetic field in the core was built up predominantly in the Carbon burning phase, because this and the subsequent phases of evolution do not last long enough for the torque to be effective.

2. If, on the other hand, the core is spinning near its stability limit, then the collapse can proceed only if the angular momentum (and rotational energy) is continuously extracted. In such a slow collapse the sequence of

configurations will always be at the stability limit. In particular, the newly born pulsar will be spinning maximally. Interestingly, there may not be an associated "supernova explosion". Since the binding energy has been extracted over a very long timescale, the disruption of the star is gradual and continual, and not explosive.

3. The third possibility is that the core is spinning rapidly, but the angular momentum is not enough to prevent the collapse to a neutron star. In this case, the resulting neutron star will be spinning rapidly. But if the binding energy released is not able to produce a "prompt" explosion (as calculat'ions seem to suggest), then the rotation of the neutron star can be slowed down by magnetic torques. Because of the very high field and rapid rotation the timescale of extracting the angular momentum and rotational energy can be sufficiently short to be able to aid or to be responsible for the supernova explosion.

REFERENCES

Ardelyan, N.V., Bisnovatyi-Kogan, G.S., Popov, Yu.P., 1979, Sov. Astr., 23,705-711

Bethe, H.A., Wilson, J.R., 1985, Astrophys. J., 295, 14-23

Bisnovatyi-Kogan, G.S., 1971, Sov. Astr., 14,652-655

Bisnovatyi-Koqan, G.S., Popov, Yu.P., Samochin, A.A., 1976, Astrophys. Sp. Sci., 41, 287-320

Bodenheimer, P., Ostriker, J.P., 1973, Astrophys. J., 180, 159-169

Burrows, A., Lattimer, J.M., 1985, Astrophys. J., 299, L19-L22

Deubner, F.L., Gough, D., 1984, Ann. Rev. Astr. Astrophys., 22, 593-619

Fricke, K.J., Kippenhahn, R., 1972, Ann. Rev. Astr. Astrophys., 10, 45-72

Howard, R. 1984, Ann. Rev. Astr. Astrophys., 22, 131-155

Kardashev, N.S., 1965, Sov. Astr., 8, 643-648

Kundt, W., 1976, Nature, 261, 673-674

LeBlanc, J.M., Wilson, J.R., 1970, Astrophys. J., 161, 541-551

McNally, D., 1965, The Observatory, 85, 166-169

Muller, R., Hillebrandt, W., 1979, Astr. Astrophys., 80, 147-154

Narayan, R., 1987, Astrophys. J., 319, 162-179

Pacini, F., 1983, Astr. Astrophys., 126, Lll-L12

Ruderman, M.A., Sutherland, P.G., 1973, Nature Phys. Sci., 246, 93

Shapiro, S.L., Lightman, A.P., 1975, Astrophys. J., 207, 263-278

Srinivasan, G., 1985b, invited lecture at the XIXth General Assembly of International Astronomical Union, New Delhi.

Sugimoto, D., Nomoto, K., 1980, Sp. Sci. Rev., 25, 155-227

Symbalisty, E.M.D., 1984, Astrophys. J., 285, 729-746

Tohline, J.E., 1984, Astrophys. J., 285, 721-728

Trimble, V., 1982, Rev. Mod. Phys., 54, 1183-1224

Woosley, S.E., Weaver, T.A., 1986, Ann. Rev. Astr. Astrophys., 24, 205-253