6.8 MULTIPLE PULSAR EJECTION IN SUPERNOVA EVENTS*

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Abstract. Fragmentation in the collapse of a supernova core, followed by energy loss in neutron star formation, is shown to lead to disruption of the resulting system. The elements of the system, some of which should be pulsars, can attain velocities of the order of 10^3 km/sec if currently quoted parameters are correct.

Although pulsar formation is generally attributed to supernova events, only two pulsars are convincingly associated with known supernova remnants (the Crab Nebula and Vela). Other pulsars are close enough to remnants to suggest association (Prentice, 1970), but only if they are moving away from the remnant at velocities of the order of 10^3 km/sec. Another problem seems to be that a supernova core may well be too massive to form a gravitationally stable object (Arnett, 1967), (e.g. 'Neutron star'), and gravitationally collapsing objects ('black holes') do not presently seem promising candidates to be pulsars.

Fowler and Hoyle (1963) suggested some time ago that the symmetric ejection of radio-luminous material from galaxies could be caused by asymmetrical processes occuring in the collapse of very massive objects. Indeed, it is known that such an imploding system is Rayleigh-Taylor unstable. Thus the more massive core could fission into several less massive objects. The same idea can be applied to a supernova event, wherein the core fragments into some distribution of neutron stars, black holes, and general debris (planetesimals, dust, etc.). The number of fragments should be few, since the disparity between core mass and neutron star masses is not large. Such a multiple system would be readily detectible either directly as superimposed pulsars or indirectly from the orbital perturbations to the observed pulsar's period. At present, there is only a suggestion (Michel, 1970; Richards *et al.*, 1970) that some pulsars have companions and then only of planetary mass.

Our point here is to show that the resultant system can be expected to become unbound, with the component objects (not all of which need be pulsars) ejected with velocities of the order of 10^3 km/sec. Consider the binary fission of a supernova core into equal mass neutron stars. The collapse time to form two stars is expected to be of the same order as the time for the two stars to fall together. Furthermore, the conservation of the angular momentum of the original core would instead place them in highly eccentric orbits as shown in Figure 1. The semimajor axis would be comparable to the initial core radius, while the closest approach distance would be determined by the initial angular momentum of the core. Since final condensation occurs at the highest system density, this will also be when the fragments are closest together.

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At closest approach, the kinetic energy relative to the barycenter can be as high as a tenth of the rest mass (for 'contact' trajectories), yet the system is only slightly bound. If now the rest mass of the system is rapidly reduced by a fraction f, the system would become unbound (Michel, 1970; Richards *et al.*, 1970; Blaauw, 1961; Michel, 1963) by f times the gravitational binding energy less the total binding energy. The velocity at infinity would then be given from

$$V^2/c^2 = GM(2f - 1 + e)/2a, \tag{1}$$

where a is the closest approach distance to the barycenter, f is the mass loss fraction,

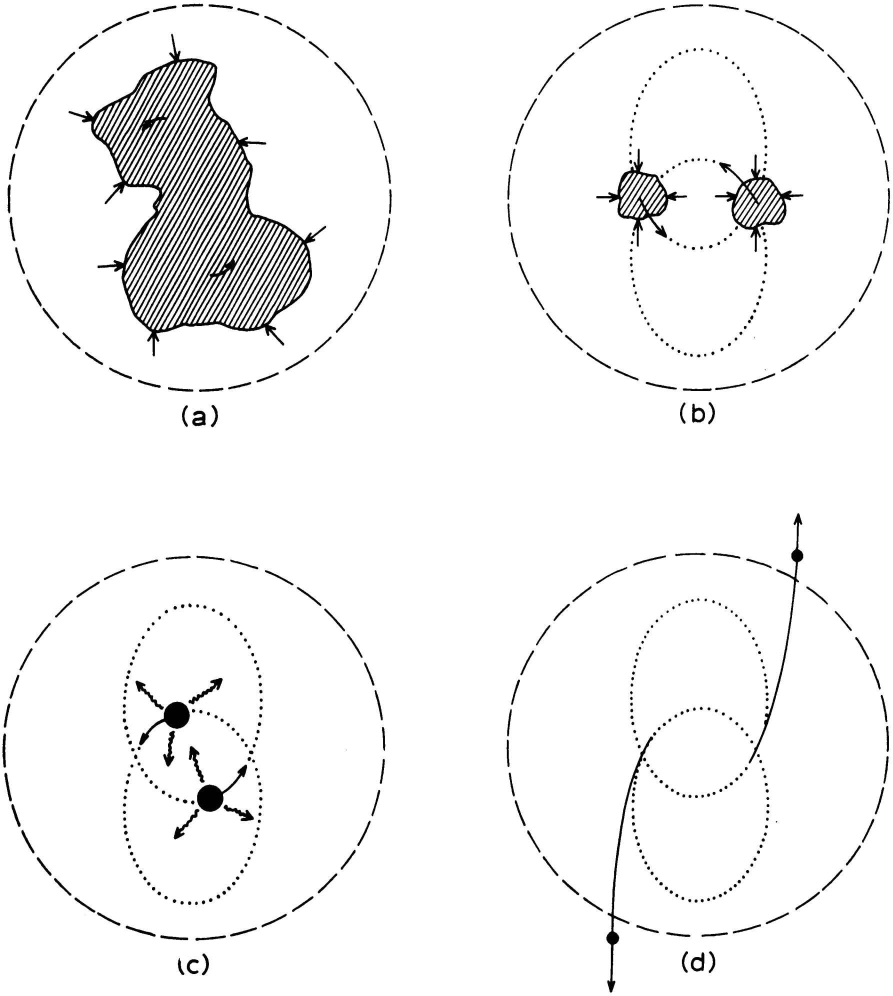

Fig. 1. Schematic development of run-away pulsars at the phases (a) Collapse and fragmentation, (b) Condensation, (c) Radiation and (d) Disruption. Dashed line shows boundary between ejected shell and collapsing core. Dotted lines show bound orbits after separation but before radiation. A complete orbit is not executed.

and e is the orbital eccentricity (nearly unity for the model described above). The eccentricity can be estimated roughly from

$$(1 - e)/(1 + e) \approx a/R_{\text{core}} \geqslant R_{\text{pulsar}}/R_{\text{core}} \tag{2}$$

which gives values for $1-e$ of about 5×10^{-3} for present supernova models. Thus escape velocities are obtained if $f \geqslant (1-e)/2$ or about 2.5×10^{-3}. If non gravitational forces between the two fragments could be neglected, we would have

$$1 - e = 2w_0^2 r_0^3/GM \tag{3}$$

where w_0 is the initial rotation frequency of the core (radians/second) and r_0 is the initial distance between the center of mass of each fragment-to-be and the total center of mass ($r_0 \approx \frac{1}{2} R_{\text{core}}$). Thus for one solar-mass objects

$$1 - e = 1.8 \times 10^{-12} w_0^2 R\ (\text{km})^3 \tag{4}$$

and for nominal values ($w_0 = 0.1$, $R = 10^3$), $1-e$ is even smaller than given in Equation (2). Since nongravitational forces must act if the closest approach is less than the neutron star diameter, 'contact' trajectories should be favoured. Note that relatively little energy is required to adjust the closest approach distance. The rest-mass energy fraction released in the neutron star formation event is perhaps of the order (Wheeler, 1966; Tsuruta and Cameron, 1966) of $f = 3 \times 10^{-2}$, which would give a recession velocity of 2×10^4 km/sec for $a = 10$ km. The mechanism is less efficient if the energy is lost slowly, and a correction may be roughly estimated using the replacement

$$f \to f^* \approx f\,(t_a/t_{\text{decay}})^{2/3}\ (t_{\text{decay}} > t_a) \tag{5}$$

where

$$t_a^2 = a^3/GM\,(1 + e) \tag{6}$$

is the time for one radian of orbital motion at periapsis, and t decay is the characteristic time to release energy in the formation event.

Figure 2 plots the values of f, e, and a required to produce runaway pulsars at a velocity in excess of 10^3 km/sec. We see that nominal energy release values and stellar dimensions permit recession velocities of the order of or greater than 10^3 km/sec. Similar ideas could be applied also to massive objects (Fowler and Hoyle, 1963; Michel, 1963).

It is not clear from the available data whether such runaway motions are required for the pulsars. The absence of observed pulsars associated with the other supernova remnants could be attributed to the formation of non pulsar objects (M. Rees, private communication) or of pulsars that are not beamed towards us. On the other hand, the mechanism proposed here seems capable of producing runaway pulsars whether they are yet required by the data or not. The detection of such objects would thereby be suggestive of fragmentation in the supernova event.

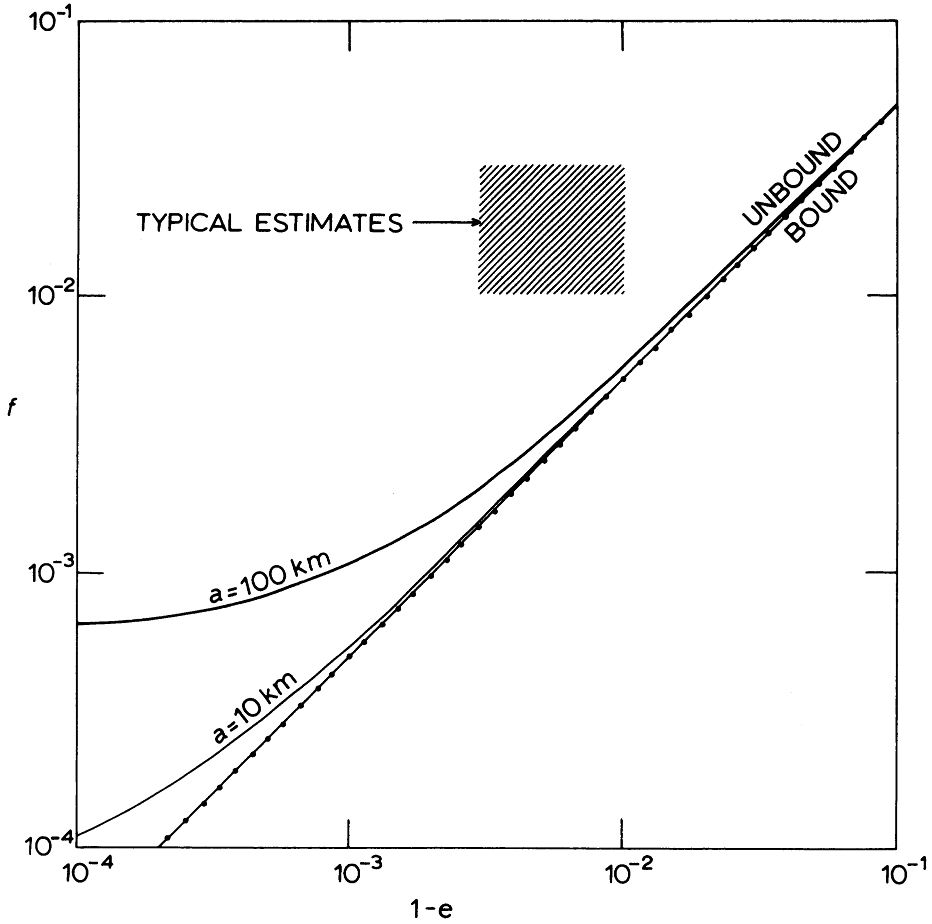

Fig. 2. Regions of f and e that permit disruption for various values of a assuming one solar mass pulsars. The mass-loss fraction f should be replaced by f^* if the emission is slow, see Equation (5). Above the solid lines for the appropriate value of a, the velocity exceeds 10^3 km/sec, while below the dotted line, the system remains bound.

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