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A Radio Pulsar in SN1987A?(*)

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Summary. — A complex three-ring shaped structure has been reported extending some arcseconds around the SN1987A central spot by several authors. This structure is believed to arise when a thin shell of matter surrounding the supernova was illuminated by the initial extreme-ultra-violet flash from the explosion of the progenitor. In this view the two ring-shaped outer loops, $\sim 3''$ in size, are interpreted as limb brightening of an hourglass-shaped nebula surrounding the supernova, while the smaller central ring is located at the waist of the hourglass. Our explanation of the two external loops is different: keeping the hourglass-shaped nebula scenario, we believe that these loops result from the interaction of this nebula with a double beam of relativistic particles emitted by a young pulsar formed by the supernova.

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1. – Introduction

The two outer loops near SN1987A were discovered in the O_{III} ($\lambda = 5007$ Angstroms) band and in a continuum band centered at $\lambda = 6067$ Angstroms at the Las Campanas Observatory ~ 750 days after the explosion [1]. Subsequent observations performed at the same observatory and at La Silla with the NTT telescope until December 1989 [2, 3] confirmed the loops at the same position and showed some decay in their brightness. In february 1994 optical images were taken with the repaired Hubble Space Telescope (HST) [4]. The high quality of these images showed clearly that these outer loops are part of two great elliptical rings not centred on the supernova (SN). Adopting an inclination angle for the line of sight of about 45°, these rings reduce to near circular, displaced from the central source. The centres of these rings and the centre of the smaller, brighter ring visible between them (which is coincident with the SN spot) nearly lie on the same axis. These features led to the following scenario proposed by several authors [5-7] to explain

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this three-ring structure: the three rings are parts of an hourglass-shaped nebula surrounding the SN illuminated by the flash produced in the SN explosion. The nebula was formed when a fast wind ($v \sim 500$ km/s), emitted by the blue supergiant progenitor of the SN, interacted with a more slower wind ($v \sim 10$ km/s), emitted by the same star in an earlier red supergiant phase [8]. Some detailed computations of this two-wind interaction showed some difficulties for this model. In particular the hourglass shape is obtained only assuming an *ad hoc* enhancement in the density of the red supergiant wind along the equatorial plane of the star. Moreover, in all the models proposed, this density enhancement should be extremely high and the resulting expansion speed for the central ring is systematically higher than the measured value of ~ 10 km/s [9, 10]. These difficulties are solved if it is assumed, as recently suggested [11], that the central ring is the inner rim of the relic of the primordial cloud out of which the SN progenitor was formed. In both these kinds of scenario the outer loops result either from the limb brightening of a thin shell of matter resulting from the interaction of the two winds, or from the brightening of those parts of it that are simultaneously reached by the SN flash. Both these conclusions are affected by serious difficulties, in particular: if the outer loops are a limb-brightened feature, a smoothly fading (but observable) surface brightness should appear in the interior of the loops. This light is associated with those parts of the shell observed face-on. This feature is, for instance, visible in the simulated image of the shell emission produced by Wang and Mazzali [6]. Indeed this tenuous light is not visible in the HST image, where the two outer loops are clearly ring-shaped. If the outer loops result from those parts of the shell simultaneously visible at the present time from Earth, their size should clearly evolve with time. Crotts and Kunkel [3] predicted that these rings should have begun to shrink by 1991 for finally disappear in 1992. The HST 1994 image shows that this is not the case and comparison with other images previously taken shows that the position of the outer loops has remained practically unchanged throughout several years.

2. – The pulsar model

What the HST image shows is that the outer loops are ring-shaped and not evolving features. For the reasons outlined above, this seems to rule out any association of these features with a radiation more o less isotropically distributed in space as any radiation coming from the SN explosion. To solve this puzzle we propose that the outer rings result from the illumination of the hourglass-shaped nebula by the highly beamed emission from the magnetic poles of a pulsar formed from the SN explosion. This hypothesis is in accordance with the 13 s duration of the neutrino burst from the SN1987A that suggests that a neutron star rather than a black hole was formed in the progenitor collapse [12]. The fact that no pulsed emission has been detected yet from SN1987A is explained, in our model, by the system geometry itself: the orientation of the pulsar beam with respect to the line of sight, as deduced from the outer rings orientation, is such that it may be hard to detect any pulsed signal from Earth. In our scenario the spin axis of the neutron star coincides with the symmetry axis of the rings. Reasonably assuming that the pulsar spin axis is the same as the progenitor's, the inner ring results naturally placed in the equatorial plane: a condition required in both the scenarios suggested by the origin of the inner ring. A constraint on the nature of the blue supergiant phase wind can be derived from the detailed structure of the outer rings. The HST image of these rings shows a relatively smooth structure with some clumpy features clearly visible. These features can be ascribed to the onset of some instabilities in the shell. Chevalier [8] has suggested that a dense shell accelerated by the hot, low-density gas of the fast blue supergiant phase wind

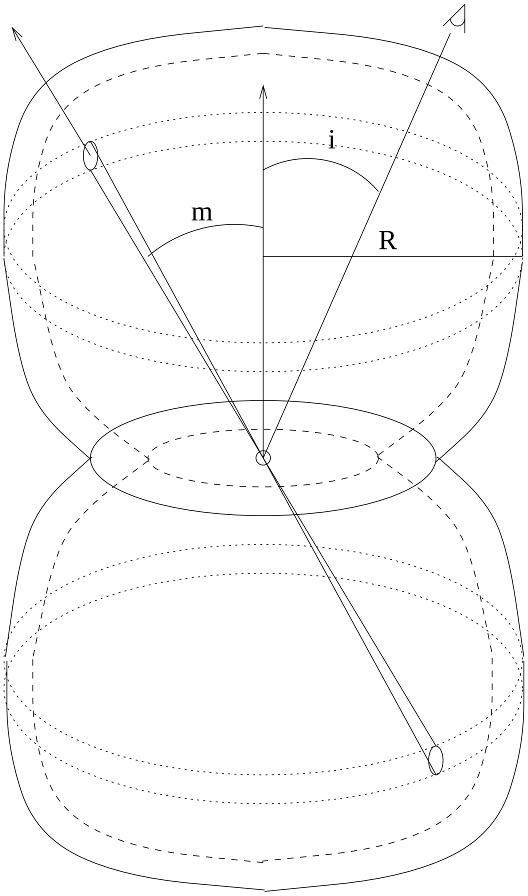

Fig. 1. – A schematic view of the region around SN1987A in the model discussed in this paper. m is the angle between the magnetic axis and the spin axis of the pulsar, i is the inclination of the spin axis with respect to the line of sight.

is Rayleigh-Taylor unstable, and clumping within this shell is likely. In detailed hydrodynamical computations Blondin and Lundqvist [7] showed that shear (Kelvin-Helmholtz) instabilities can take place in the lobes of the shell because of the rapid flow of the gas within the lobes. Very strong dynamical instabilities resulting from thermal cooling are found by the same authors: enhanced radiative cooling of the blue supergiant phase wind removes the isotropic thermal pressure that would smooth out any perturbation growing in the shell. So, from the relatively smooth structure of the rings we can conclude that the blue supergiant phase wind is, at least, partially adiabatic.

Our model is sketched in fig. 1. A deeper discussion of this model is given in another paper [13]. There, in particular, some asymmetries observed in the HST image of the rings (*e.g.* the different eccentricity of the upper and the lower outer rings and the slightly offset position of the centres of the rings with respect to the symmetry axis of the system) are used to constrain the system geometry. This allowed us to compute the physical distance between all the different parts of the system in terms of the value of the inclination of the symmetry axis to the line of sight and of the physical size of the inner ring (accurate

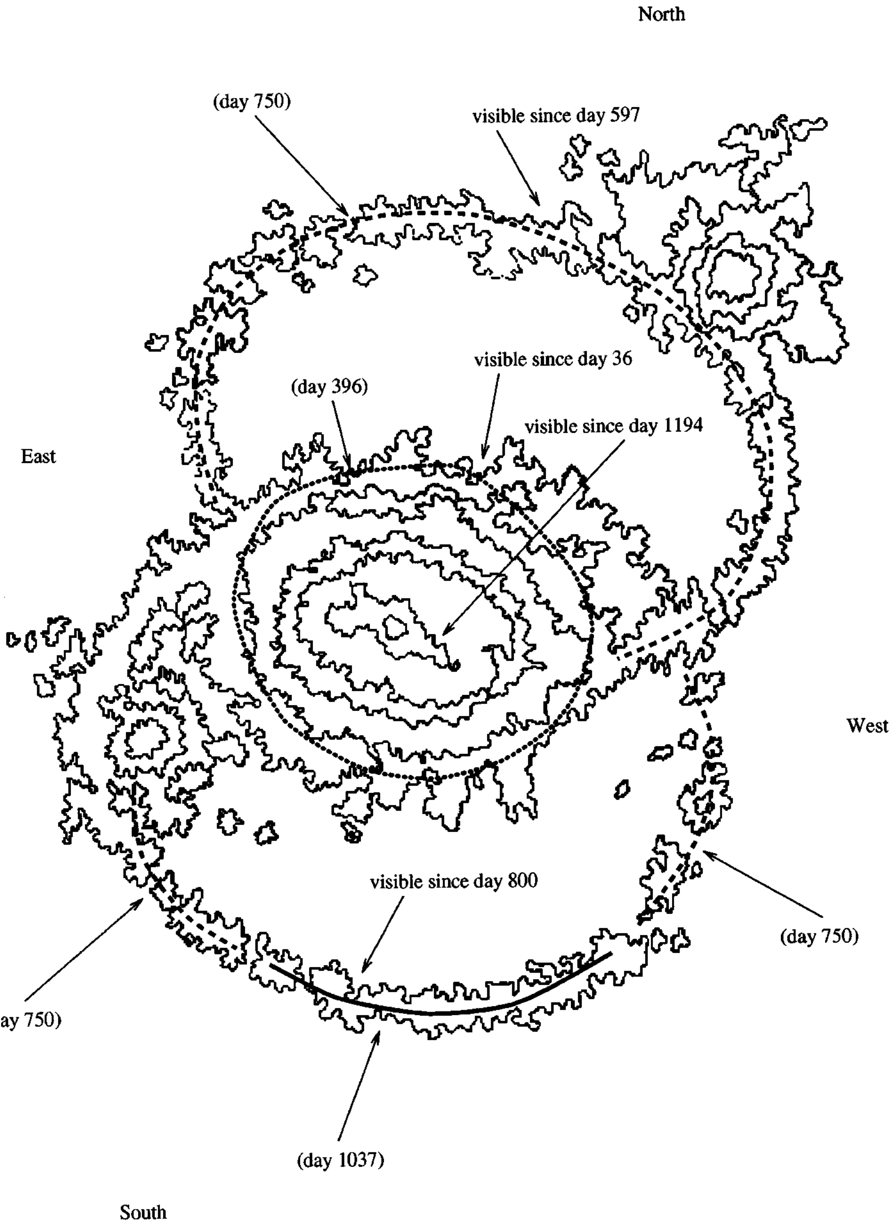

Fig. 2. – A sketch of the HST image of the SN1987A taken in February 1994. The dotted line indicates the inner ring structure (with the northern rim of the nearer outer ring overlapped) first seen at ESO [2]; the dashed lines indicate parts of the outer rings first seen at Las Campanas Observatory [1]; the solid line indicates part of the outer rings first seen by the NTT telescope [14]. The numbers in brackets are the times (computed in days after the explosion) at which these observations were made; the numbers without brackets are the time delays from the nearest and farthest point of each outer ring computed with our model.

estimates of these two values are given by some authors [15,16]). The results of this analysis constrained our model because the time delays with which different parts of the outer loops become visible from Earth (in the limit hypothesis that the pulsar "switched-on" immediately after the SN explosion) should agree with the epochs at which the outer loops were actually first seen. Here the results of this analysis are shown in fig. 2. Our analysis gives also an estimate of the angle between the magnetic axis and the spin axis ($\sim 50°$) and an upper limit for the angular width of the pulsar beam ($W_{\rm core} \leq 5°$) (this last value is deduced from the upper limit of the outer ring thickness, assuming that the thickness of the rings reflects the thickness of the beam itself). This value allowed us to give an estimate of the pulsar period. Some recent works by Rankin [17-21] suggest that young pulsars are characterised by the presence of a "core component" beam with typical opening angles of some degrees. The width of this beam is linked to the pulsar period *via* the formula $W_{\rm core}(\text{degrees}) = 2.45°(P_{\rm pulsar}(\text{s}))^{-1/2}$ [20]. Our estimate gives $P_{\rm pulsar} \sim 0.2$ s in agreement with the theoretical scenario in which the pulsars are born with slow periods ~ 100 ms [22]. If our hypothesis is correct this system offers the opportunity of studying the early evolution of a young pulsar beam.

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