Simultaneous Modelling of the Complete SN1993J Expansion and Radio Light Curves

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Abstract We report on our modelling of all the available VLBI data and radio light curves of supernova SN1993J. For this purpose, we have used all the available radio light curves and we re-analyzed all the available VLBI observations of this supernova. We have obtained the most complete expansion curve of a supernova ever, which spans more than a decade at several frequencies. For the data modelling, we have developed a new software capable of simulating the evolution of the radio emission of a supernova. We find that for explaining both the radio light curves and the expansion curve simultaneously, a radial structure of the magnetic field inside the radiating region and opacity effects from the ejected material have to be considered, along with a constant pre-supernova mass-loss rate (contrary to results reported by some authors).

1 Introduction

Radioemission has been detected only from type II/IIb and Ib/c supernovae, which appear to be the result of gravitational collapse of massive stars. R.A. Chevalier [2] proposed a model, now called the *Standard Interaction Model (SIM)*, to explain the radioemission from supernovae based on a hydrodynamical model of the expanding ejecta. This model explains most of the observations, with the exception of some subtle details which are not yet well understood. Some modifications of the model basic assumptions may be necessary.

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In the SIM, a strong interaction between the high velocity expanding supernova ejecta and the ionized circumstellar medium (CSM) is expected, resulting in the formation of a self-similarly expanding shell-like structure. Within the shell, the circumstellar thermal electrons are accelerated up to relativistic energies and spiral along the lines of amplified magnetic fields (possibly originated close to the contact discontinuity), generating radio synchrotron emission which is detected at centimeter wavelengths. The radius of the shell structure is proportional to t^m, where t is the supernova age and m is the deceleration parameter.

2 RAMSES

We have created a new code named RAMSES (*Radiation-Absorption Modelling of the Synchrotron Emission from Supernovae*), which is described in detail in [8]. RAMSES is capable of simulating the radio light curves and expansion curve of a supernova taking into account several cooling effects of the electron population, as well as synchrotron self-absorption and a finite electron meanlife time inside the shell. RAMSES evolves all the hydrodynamic variables of a supernova according to the SIM and is capable of comparing the results from the simulations with observational results, performing a χ^2 minimization analysis in order to obtain the best-fit estimates of all the parameters that describe the physical conditions in which the supernova evolves.

3 Supernova SN 1993J

Supernova 1993J was discovered in the galaxy M 81 ($\sim$3.6 Mpc away, see Freedman et al. [5]) on 28 March 1993 by Francisco García [11]. This supernova has been widely observed in many bands of the electromagnetic spectrum. In the radio band, its flux density evolution at many frequencies has been monitored with several instruments and hundreds of flux density measurements are available. Moreover, it has been a target of VLBI observations for more than a decade, with a total of 69 global observing epochs between April 1993 and November 2005.

3.1 VLBI Expansion Curve

We show in Figure 1 the expansion curve of SN 1993J resulting from the analysis of all the VLBI data, using refined calibration strategies and new analysis tools (see [8] and [9] for more details). From this expansion curve, we find that the shell sizes measured at 1.6 GHz are systematically larger than those at higher frequencies. Indeed, data at 1.6 GHz follows an expansion curve that differs from that cor-

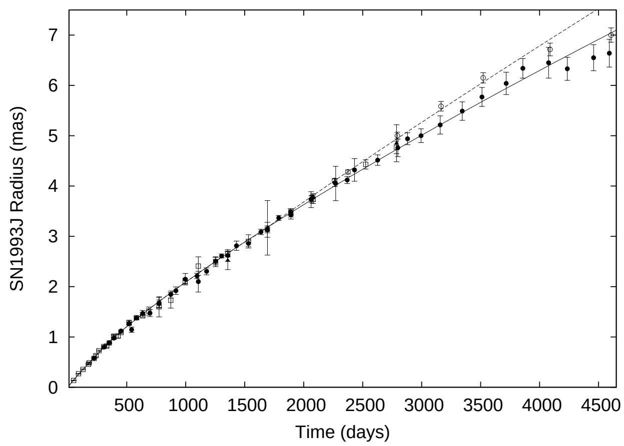

Fig. 1 Expansion of SN 1993J resulting from the analysis of all the available VLBI epochs. Empty squares are data at 8.4 GHz; filled circles, data at 5 GHz; triangles, data at 2.3 GHz; and empty circles, data at 1.6 GHz. The dashed line corresponds to an expansion model with one expansion index, fitted to 1.6 GHz data (except the last, too low, data point). The solid line is a model with two expansion indices (see text), fitted to the data at higher frequencies (except the three latest, too low, data points).

responding to 4.9 GHz, 8.4 GHz, and 2.3 GHz. The SN 1993J expansion curve using all data but 1.6 GHz data can be well modelled using two expansion indices ($m_1 = 0.928 \pm 0.010$ and $m_2 = 0.795 \pm 0.005$), corresponding to two different expansion regimes separated by a break time ($t_{br} = 390 \pm 30$ days after explosion). The expansion curve at 1.6 GHz can be well modelled using one single expansion index, $m = 0.87 \pm 0.02$ (we do not have 1.6 GHz data at epochs earlier than the break time at day 390). These expansion results are quite different from those published by [1] and similar to those to be published in [7].

3.2 Radio Light Curves

Weiler et al. [12] reported on a complete flux density monitoring of SN 1993J at several frequencies through its detectable lifetime. These authors found relatively good agreement between the data and their parametric model, but had to introduce some corrections to the SIM model to be able to explain an enhanced (exponential-like) flux density decay at late epochs. These authors interpreted such a decay as an increased radial drop of the circumstellar electron density. However, as we explain in [8] and [9], such a density drop is not sufficient to explain all the flux density decay at late epochs. A finite meanlife time of the electrons inside the shell (that would act, not only during the latest epochs, but during the whole expansion) is necessary to account for the observed exponential flux density drop. We show in Figure 2 the best-populated radio light curves reported by Weiler et al. [12], together with our best-fit RAMSES model (see more details in the next section).

4 SN 1993J and RAMSES: Beyond the SIM Model

RAMSES allows us to explain, simultaneously, the frequency-dependent deceleration parameter found in our SN 1993J expansion curve and the peculiarities of the radio light curves reported in [12]. These explanations (given in [7] and described in more detail in [8] and [9]) imply that the real expansion index of SN 1993J at late epochs is close to the one obtained at 1.6 GHz, while the lower expansion index obtained at higher frequencies is caused by different biases related to structure effects and to the finite sensitivity of the VLBI interferometers.

On one hand, if the amplitude of the magnetic field inside the radiating shell decays radially, the limited sensitivity of any interferometric array will introduce a measurable difference of the source size between 1.6 GHz (where the dynamic range of the images is higher) and all the other frequencies (where the dynamic range is lower and a fraction of the outer shell will fall below the thermal noise cut). Given that the supernova flux density decreases with time and the sensitivity of the VLBI interferometers remains roughly constant, this size discrepancy at different frequencies will increase with time (as we find in our VLBI expansion curve). Moreover, the exponential drop of flux density after day 3100 reported in [12] (and simulated by RAMSES using a constant electron meanlife and an enhancement of the radial drop of the circumstellar electron density) would also translate into a progressive, and quite fast, underestimate of the shell sizes at all frequencies. This effect would explain the extremely small shell sizes that we obtain for our latest VLBI observations, when compared to our model predictions (see Figure 1).

On the other hand, a progressive decrease of the ejecta opacity to the radiation at higher frequencies can also help to explain the shell size discrepancy between different frequencies. The bias of any shell-size estimate is a function of the ejecta opacity, no matter the method used for such an estimate (being, however, the method used in [7], [8], and [9] more stable than modelfitting to the visibilities under changes in the supernova structure, as it is explained in these publications). Such an ejecta opacity decrease (relevant at 5 GHz but not at 1.6 GHz) also helps to explain the slight bump in the flux density evolution at high frequencies, around day 1500 after explosion, that can be seen in the radio light curves. This small bump was not well modelled in [12]. The evolution of the ejecta opacity here proposed could be physically explained if the opacity mechanism is due, for instance, to free-free processes.

The RAMSES model assumes a standard circumstellar density profile (i.e., with $s = 2$). The temperature of the thermal circumstellar electrons is also assumed to decrease as the distance to the explosion center increases. This assumption is needed in order to explain the radio light curves in the early epochs. The electron distribution with $s = 2$ is similar to that one used in [4] (where a radially-decreasing temperature was also used) and is originated by a constant pre-supernova mass-loss rate and stel-

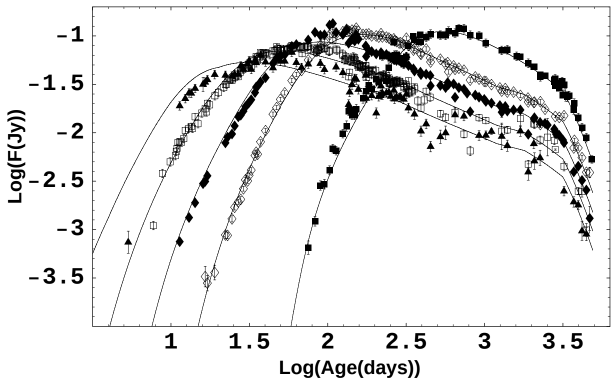

Fig. 2 Light curves of SN 1993J taken from the best-populated data sets of [12], superimposed to simulated results from RAMSES (solid lines), using the expansion model described in Section 4. Filled triangles are data at the wavelength of 1.2 cm; empty squares, data at 2 cm; filled diamonds, data at 3.6 cm; empty diamonds, data at 6 cm; and filled boxes, data at 20 cm. A progressive lifting of the ejecta at all wavelengths but 20 cm, beginning on day 1200 and ending at day 1500, has also been used in these simulations, together with an enhancement of the radial circumstellar density drop (from $\rho \propto r^{-2}$ to $\rho \propto r^{-4}$) from day 3100 onwards (see text).

lar wind. Using a different value for s (like those proposed by [10] or [3], which are more close to $s = 1.6$) results in a much poorer agreement between the observations and the RAMSES model.

5 Conclusions

We report on the complete analysis of all the VLBI observations of supernova 1993J. We also report on RAMSES, a new code for simultating the evolution of the radio emission of a supernova. This code is capable of fitting a set of physical parameters to the expansion curves and radio light curves of a real supernova.

Combining the radio light curves and the expansion curve of SN 1993J with RAMSES simulations, we conclude that the supernova expansion scenario can be well modelled using only two expansion regimes (up to four regimes were used in [1] to model the expansion curve) without the necessity of introducing any time evolution of the pre-supernova stellar wind (or mass-loss rate), nor any clumpy medium added to the homogeneous circumstellar medium. Instead of these assumptions, we can model all the observed data (light curves and expansion curve) by taking into account the radiative losses of the electron population inside the shell, a radial dependence of the thermal electron temperature, which would decrease as the distance to the explosion center increases, and a radial drop of the amplified magnetic fields inside the shell. This latest assumption in the model (together with the finite sensitivity of the interferometers and a progressive lifting of the ejecta opacity at higher frequencies) would explain the different shell sizes obtained from our VLBI observations at different frequencies. A finite meanlife of the electrons inside the radiating region and an enhanced radial drop of the circumstellar density beyond day 3100 after explosion would also explain all the peculiarities of both, radio light curves and expansion curve, at late epochs.

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