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Statistical analysis of Core-Collapse explosion parameters: An astrophysical probe for Supernova neutrino flux

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Summary. — Core-Collapse (CC) Supernovae (SNe) are among the most extreme and luminous astrophysical phenomena, besides sites of intense neutrino production and particle acceleration. The electromagnetic observations of these transients allow us to characterize the explosion energy and the configuration of the progenitor star at the explosion time. This information provides an important constraint in the SN neutrino flux in terms of energy, flavor, and intensity. The launch of the Legacy Survey of Space and Time and other future dedicated optical surveys are going to open the possibility to perform statistical studies on the CC SNe parameters. These studies need sufficiently fast and accurate procedures for the characterization of SN events. In this framework, we have developed semi-/analytical models and Bayesian modeling procedures, which reconstruct SN Light Curves and infer the main explosion parameters connecting them with the expected neutrino spectrum.

1. – Introduction

The explosion of a Core-Collapse (CC) Supernova (SN) is a catastrophic event that represents the final evolutionary stage of stars with masses at the Zero Age Main Sequence(1) larger than $\sim 8-10 M_{\odot}$(2). These explosions achieve brightness comparable to that of their host galaxy ($\sim 10^{41-42} erg/s \simeq 10^{8-9} L_{\odot}$, see fig. 1), becoming responsible for the formation of compact objects as well as the emission of gravitational waves and particles like neutrinos and cosmic rays. The discovery of the neutrinos immediately after the CC of SN 1987A, indeed, has confirmed the neutrino-driven explosion mechanism, thus opening the doors of a new astronomy and motivating the research of other

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(1) Generally abbreviated ZAMS, it occurs when the so-colled H-burning ignites in the stellar core and the star arrives in the main sequence, an evolutionary phase characterized by hydrostatic equilibrium for the star, see [1].
(2) The $\odot$ symbol marks quantities that are related to the Sun, *e.g.*, the Solar mass $M_{\odot} \simeq 1.99 \cdot 10^{33} g$, radius $R_{\odot} = 6.96 \cdot 10^{10} cm$ and luminosity $L_{\odot} \simeq 3.83 \cdot 10^{33} erg/s$.

Fig. 1. – SN 2023ixf in M101 galaxy on 27 May 2023, is among the closest CC SNe of the last several decades ($d_L = 6.9 Mpc$); its early spectra have revealed an intense CSM-ejecta interaction, likely linked to a delayed neutrinos emission. Image taken by G. Cassarino.

neutrino extragalactic sources. Although CC SNe play an important role in many astrophysical domains, ranging from cosmology to multimessenger astronomy, there are still basic issues to be answered, mainly related to the extreme variety of their electromagnetic features. In fact, SN events are marked by a huge heterogeneity of spectroscopic and photometric behaviours, which are the result of a different configuration of progenitor star and the explosion energy [2,3]. Therefore, statistical studies on these features could help us to understand not only the fate of massive stars (MS), but also the SN neutrino flux produced during their explosions or, later because of the interaction between the Circumstellar Material (CSM) and the ejecta (the stellar material ejected after the CC).

2. – Supernova characterization

The SN characterization aims to identify the physical configuration of stars at explosion as well as the nature of mechanisms responsible for their brightness during and after the explosive phase following the CC. In many cases, the analysis of the spectrophotometric observations enable us to constrain the kinetic energy (E) and the mass (M_{ej}) of the ejecta together with its chemical composition and the progenitor's radius at the explosion (R_0). However, the inference of these physical properties from the data requires important theoretical efforts for the modeling, whose approaches can be itemized in three categories, as follows:

- *Hydrodynamical Models* consider nuclear and atomic details for the ejecta's modeling, using sometimes a general relativistic approach (see *e.g.* [3]). They require more computational resources and time than the other less accurate methods;
- *Scaling Equations* are the result of physical approximations that limit their validity and applicability only to SNe of the same class. However, they are very easy-fast to use and useful to characterize wide samples of SNe (see *e.g.* [4]);
- *(Semi-)Analytical Models* represent the best compromise between accuracy and computational cost and can be used to build fast-accurate modeling procedures [5].

Regardless of the chosen approach, when considering supplementary sourcing mechanisms capable of sustaining the electromagnetic emission of the ejecta, it is necessary to add other modeling parameters. They include the mass of radioactive elements such as ^{56}Ni (M_{Ni}) and, in the case of ejecta-CSM interaction, the parameters describing the CSM features like its mass (M_{CSM}) and its radial extension (R_{CSM}).

The launch of the Legacy Survey of Space and Time (LSST), along with other upcoming dedicated optical surveys, will enable the opportunity to conduct statistical studies on these parameters. Within this context, we have devised semi-analytical models and refined scaling equations that allow us to extract the primary explosion parameters from SN Light Curves (LC) and their spectral characteristics [4]. The diffuse SN neutrino background is often affected by the uncertainties of the stellar evolution models and the initial mass function (see *e.g.*, [6]), therefore, an extended statistical approach to the SN characterization could establish a more direct connection with expected neutrino flux.

3. – Neutrinos from CC-Supernovae

According to the MS evolution theory, MS typically manage to complete all burning cycles until to get an iron core. A core of this type is unable to provide enough energy to sustain the structure and therefore begins to collapse on itself. Whereas the star becomes unstable, a high flux of neutrinos emerges from the collapsing core heating the innermost and densest stellar layers with only $\sim 1\%$ of the neutrinos' carried total energy (see *e.g.* [7] and reference therein). Actually, these neutrinos in MeV energy range are the unique channel to directly observe the CC "explosive" phase, the ignition spark of the spectacular death for MSs. However, the information related to the global thermal energy ($k_B T_\nu$) and the luminosity (L_ν) of these neutrinos directly influence the deposition of energy in the upper stellar layers:

$$(1) \qquad E \simeq 9.4 \times 10^{50} erg \times \left(\frac{k_B T_\nu}{4MeV}\right)^2 \times \left(\frac{L_\nu}{3 \times 10^{52} erg\ s^{-1}}\right),$$

which is quickly converted in kinetic one and becomes measurable thanks to the optical observations of "post-explosive" SN evolution (see sect. **2**).

On the other hand, before the CC explosion, the star could undergo significant mass loss phenomena, thereby increasing the mass of its CSM. After the explosion, the ejecta can impact its external CSM, leading to a "delayed neutrino emission" as a result of the interaction between the two media. When the faster-expanding ejecta collides with the CSM, indeed, two shock wave fronts start to propagate inside them, in reverse and forward ways respectively. Both shocks contribute to the acceleration of particles, but the protons' energy efficiently increases only when the forward shock propagates inside the optically thin regions, like in the low-dense CSM. The collisions between accelerated protons and the nuclei of CSM swept by the shock, produce η and π mesons which decay in high-energy neutrinos (HE$-\nu$, $TeV - PeV$) and gamma rays. The duration of this HE$-\nu$ emission (t_f) is as longer as the CSM radius is extended:

$$(2) \quad t_f = \frac{R_{CSM}}{v_{ej}^t} \cdot \left[\frac{(n-4)(n-3)}{(4-s)/(n-\delta)} \cdot \frac{M_{CSM}}{M_{ej}}\right]^{\frac{1}{n-3}} \quad \text{with} \quad v_{ej}^t = \left[\frac{2(5-\delta)(n-5)E}{(3-\delta)(n-3)M_{ej}}\right]^{\frac{1}{2}},$$

and depends both on the parameters defined in sect. **2**, and the ones (n, δ, s) establishing the matter-density distributions of the ejecta and CSM (their densities are approximated as $\rho \propto r^{-x}$ with $x = s, \delta, n$ for the CSM, internal and external ejecta regions, respectively). Furthermore, the shape of the HE-ν spectra is closely linked to these parameters. For instance, the maximum proton energy rises when increasing the ejecta velocity (v_{ej}^t); and the neutrino intensity flux is mainly related to the value of M_{CSM} [8].

Table I. – *Preliminary results of the LC modeling for SN 2023ixf.*

Symbol	Values	Symbol	Values
E	$(1.8 \pm 0.5) \times 10^{51} ergs$	M_{Ni}	$(7.2 \pm 0.2) \times 10^{-2} M_\odot$
M_{ej}	$(9 \pm 1.5) M_\odot$	M_{CSM}	$(6 \pm 4) \times 10^{-2} M_\odot$
R_0	$(1.3 \pm 0.8) \times 10^{13} cm$	R_{CSM}	$(7 \pm 3) \times 10^{15} cm$
n	12	s	2.53 ± 0.03
δ	1	t_f	16 ± 2 days

4. – Consideration and further comments

To give an example of an extragalactic neutrino source, we have modeled SN 2023ixf (see fig. 1) finding the explosion parameters reported in table I (for more details see [9]).

For this event, the expected $L_\nu \simeq 6 \times 10^{52} ergs \cdot s^{-1}$ is comparable to that of SN 1987A, however, the source is about 140 times more distant and out of the detection limit for the current and future neutrino detectors (*e.g.* JUNO). Similarly, the delayed neutrino emission has a maximum energy of $150 TeV$ and an average energy flux of about $0.8 \times 10^{-9} GeV \cdot cm^{-2} \cdot s^{-1}$, roughly 2 orders of magnitude less than the nowadays IceCube's detection limit. Nonetheless, the new generation of large-volume neutrino observatories like KM3NeT and IceCube-Gen2 could detect even sources like this [10, 11].

The example of SN 2023ixf has motivated us to extend LC modeling procedures for any CC SNe and more in general to other electromagnetic transients; with the aim to conduct statistical analysis on their explosion parameters, necessary to find and/or confirm the observative links between electromagnetic and neutrino astrophysical sources.

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