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Radial distributions of Gamma Ray Bursts and Supernovæ: Clues to their progenitors(*)

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Summary. — In this paper we compare the observed radial distributions of Gamma Ray Bursts and of Supernovæ with respect to the host galaxy center. We investigate the possibility that the observed Gamma Ray Burst offset distribution (in kpc) is in fact the distribution of I-b/c supernovæ modified by the kick received by the binary system when the first supernova explosion occurs. Our analysis lends support to the scenario in which all long-duration GRBs are produced by type Ib/c SNe. We ruled out that a significant fraction of long-duration GRBs could be due to merging of compact remnants of stellar evaluation.

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1. – Introduction

Two classes of objects have been regarded as possible progenitors of long-duration gamma ray bursts (GRBs): massive stars [8] and degenerate compact binaries [5]. In recent years the existence of a tight connection between type Ib/c SNæ and long duration GRBs has been proven in a number of convincing ways [3, 6, 7]. The afterglow of GRBs has been detected in almost 60 cases, and a supernova could have been detected in more than 20 cases at $z < 1.2$, since the most luminous SNæ associated to GRBs have absolute B magnitude $M_{\rm B} \approx -20$, comparable to the one of type Ia SNæ. However, follow-up observations spectroscopically confirmed the existence of an associated SN in only 4 GRBs and detected a SN bump in the light curve for about ten more. Therefore, in most cases, no SN associated with a long duration GRB has been found. The association of long durations GRBs with *double degenerate* progenitors is based on theoretical arguments. Potential progenitor candidates include pairs of Black Holes (BHs), BH/Neutron Star (NS), NS/NS, NS/Helium Core, or Helium core/BH [2].

If most GRBs originate from the core collapse of massive stars, then their locations inside their parent galaxies are expected to match the distribution of the birth places

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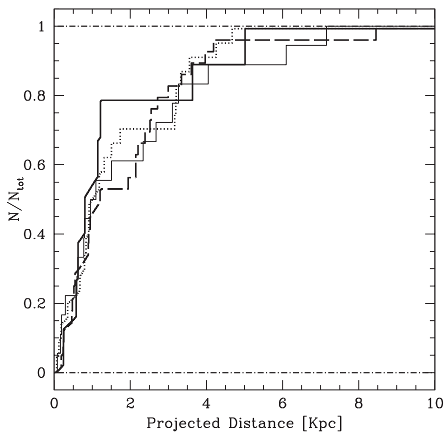

Fig. 1. – (Colour on-line) Radial distributions of supernova and GRB offsets restricted to dwarf galaxies (see text for details) in projected linear distance after Shaw bias correction. Thick green solid line: GRBs, thin solid line: type Ib/c Supernovæ, dot-dashed line: type II SNæ, dotted line: type Ia SNæ.

of type Ib/c SNæ. If GRBs originate from merging of double degenerate systems, then their locations should occur outside, several kpc away from the center of the the parent galaxies because of the kicks provided to the binary system by one or two SN explosions. With this in mind, we have compared the observed radial distribution of the offsets of the SNæ with the corresponding distribution of the offsets of GRBs measured by Bloom *et al.* [3] on Palomar, Keck and HST images complemented by two recent cases of GRBs.

2. – Data analysis

Our source of SNæ is an electronic version of the Asiago SN catalogue [1] updated to SN 2002em. We have selected all SNæ occurred in spirals or later morphological types (de Vaucouleurs types $T \geq 1$) for which the following data are reported: i) angular offset to the center of the galaxy; linear offsets in kpc are obtained from angular offset assuming that the galaxy is a flat system observed at the inclination reported in the Asiago SN catalogue; ii) radial velocity of the parent galaxy, iii) spectroscopic classification (type Ia, type Ib and Ic considered together, type II); iv) apparent major isophotal diameter of the host galaxy; v) recessional velocity, which we limited at 3000 km s^{-1}. vi) An additional restriction to effective radius $R_e \leq 2.5$ kpc has proved to be necessary since most GRB hosts are "dwarvish" irregular galaxies. This restriction leaves 20 type Ia, 8 type Ib/c, and 25 type II SNæ. If SN hosts R_e are not limited to 2.5 kpc, the difference between host galaxy size becomes *highly* significant for all three SN types, making the comparison of SN and GRB radial distribution meaningless.

3. – Comparing the radial distributions

SN radial cumulative distributions for dwarf hosts ($R_e \leq 2.5$ kpc) are compared with 17 GRBs offsets in fig. 1 after correction because of supernova losses in the innermost 1 kpc (Shaw bias, ≈ 20 % of the total number). Due to small number statistics differences between SNæ and GRBs are not significant. However, it seems that the GRB distribution is slightly offset from the center with respect to type-Ib/c SNæ *i.e.* GRB show a slight trend to occur farther out from the nucleus than type Ib/c SNæ. Could it be that the GRB is a modified type-Ib/c SN radial distribution, with a fraction of systems yielding a type-Ib/c SN event diffusing at larger distance in the host galaxy?

4. – Modified radial distribution

Binary systems may merge in locations that are significantly displaced from the location of the first SN as an effect of the kick velocity. The final GRB distribution will be, if this assumption is correct, the initial type Ib/c distribution modified by the events that occur at merging time. After the SN blast a binary (which we assume remains bound) travels across the galaxy by $d \sim 0.1 t_{\mathrm{My_r}} v_{100\,\mathrm{km\,s^{-1}}}$ kpc (where t is the merging time in $\mathrm{My_r}$, and v is the kick velocity in units of $100\,\mathrm{km\ s^{-1}}$). The most frequent coalescence channel of GRB progenitors is given by a double neutron star ($\approx$ 50%). Around 20% of NS-NS systems have $t \gtrsim$ 10 $\mathrm{My_r}$. Assuming a kick velocity of $100\,\mathrm{km\ s^{-1}}$, d can be well 1 kpc for $\sim 0.2 \cdot 0.5 \cdot g \sim 5\%$ of GRB progenitors (for $g \approx 0.5$), where g is the fraction of GRB progenitors due to coalescence of compact stellar remnants. In the case of a Helium core-BH binary, the evolutionary time is $\approx$8 $\mathrm{My_r}$, again yielding $d \sim 1$ kpc for $\sim$ 10 % of GRB progenitors. Therefore, our assumption can qualitatively explain the difference in shape between the GRB and the type Ib/c SN cumulative radial distributions which appear indeed displaced by $\Delta \sim 1 - 2$ kpc for 10–20% of sources.

A model computation [4] predicts cumulative GRB distributions as shown in the right panel of fig. 2. The computations assume that: 1) all type Ib/c SNæ originate in binary systems, from the most massive stars; 2) a first GRB event is concomitant in time and space to the type Ib/c SN; 3) a second GRB occurs due to the merging of the binary system components; 4) the kick velocity is isotropic, so that it is appropriate to consider an average velocity projected onto the host galaxy plane; 5) the velocity distribution is double Maxwellian; 6) GRBs are produced through the four merging/evolution channels listed in the Introduction [2]. See fig. 2 (left panel) for a sketch of our model. In the case of an equal percentage of SNæ and merging progenitors ($g = 0.5$), the agreement is good considering the many simplification in our calculations, the large uncertainty in the progenitor coalescence rate, and small number statistics: one more GRB discovered at $\sim$ 10 kpc from the host galaxy center would lead to an almost perfect overlapping of the two curves. The theoretical curve seems to predict an appreciable fraction of merging at fairly large radii which may be tested as the number of followed-up GRB afterglows increases. While the channels involving an He star do not yield large displacements ($\gtrsim$ 2 kpc), the converse is true for the merging of neutron stars and BHs and also for the merging of NS couples. Their merging time distributions entail a significant number of objects with time $\sim 10^8$–10^9 y, therefore allowing the system to cover large distances after the kick due to the type-Ib/c SN explosion(s). The observed GRB distribution seems to rule out the extreme case where GRBs are due to coalescence of compact objects *only* ($g = 1.0$) since fewer than observed GRBs are expected in the central regions of the host galaxy.

5. – Main results and interpretation

The GRBs and SNæ Ib/c distributions match each other within the inner first kpc, which includes about 50% of the objects. From 1.5 kpc from the host center, the GRB distribution tends to populate more the outer regions of the host galaxies with respect to SNæ Ib/c. The best fit between the observed GRB distribution (solid line) of the linear offsets and the analogue distribution of SNæ Ib/c, modified by the SN kick (thick dashed

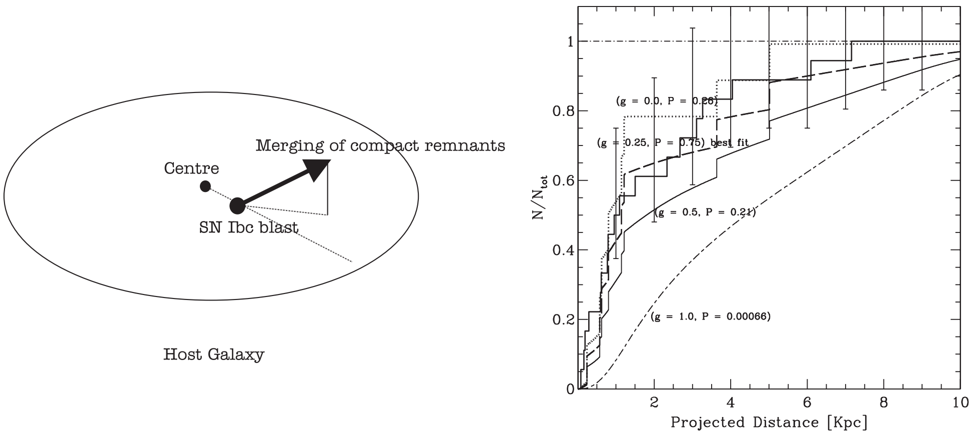

Fig. 2. – (Colour on-line) Left Panel: Sketch illustrating the main assumptions of our model computation: a first GRB occurs concomitantly with a SN Ib/ c blast. Following the blast, the binary systems moves away (not necessarily in the plane of the host galaxy) until the two compact remnants merge, producing a second GRB. Right Panel: Comparison of observed cumulative radial distribution of GRBs (green solid line with error bars) and the ones computed according to the model described in the text, for different values of the frequency of binary merging progenitors g. Error bars show non-propagated, Poisson 1σ uncertainties. In the case $g = 0.5$ (solid line; equal frequency of mergings and type Ib-c SNæ as progenitors) the agreement with observations is good considering that one more GRB discovered at $\sim 10\,\text{kpc}$ from the host galaxy center would lead to an almost perfect overlapping of the two curves. A "best fit" line (dashed red line) obtained for $g = 0.25$ is also shown. The case $g = 1.0$ (long-short dashed line) seems to be ruled out, while the case of "only type Ib/c SNæ" (dotted line, $g = 0.0$) is still acceptable.

line) would suggest that mergings may represent $\approx 25\%$ of the GRB events. However, the present data are consistent with the case that all long duration GRBs are produced by type Ib/c SNæ ($g = 0.0$, Kolmogorov-Smirnov probability 0.26). On the other hand, the same data exclude that mergings represent the major class of progenitors for long duration GRBs.

The Swift mission and SN surveys currently in progress will increase both the GRB and SN databases within the next 4-5 years, allowing to test our ideas on GRB progenitors on more robust empirical basis.

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