Implications of GRB 130603B and its macronova for r-process nucleosynthesis

Tsvi Piran1,1 Oleg Korobkin2,1 and Stephan Rosswog21
11 Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel
2Department of Astronomy and Oskar Klein Centre, Stockholm University, AlbaNova, SE-10691 Stockholm, Sweden
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The tentative identification of a Li-Paczynski macronova following the short GRB 130603B indicated that a few hundredths of a solar mass of neutron star matter were ejected and that this ejected mass has radioactively decayed into heavy r-process elements. If correct, this confirms long standing predictions [1] that on the one hand, sGRBs are produced in compact binary mergers (CBMs) and on the other hand that these events are significant and possibly dominant sources of the heavy (A > 130) r-process nuclei. Assuming that this interpretation is correct we obtain a lower limit of 0.02m⊙ on the ejected mass. Using the current estimates of the rate of sGRBs and with a beaming factor of 50, mergers associated with sGRBs can produce all the observed heavy r-process material in the Universe. We confront this conclusion with cosmochemistry and show that even though such events are rare, mixing is sufficient to account for the current homogeneous distribution of r-process material in the Galaxy. However, the appearance of significant amounts of Eu in some very low metallicity stars requires that some mergers took place very early on, namely with a very short time delay after the earliest star formation episodes. Alternatively, an additional early r-process source may have contributed at that early stage. Finally, we note that evidence for short lived 244Pu in the very early solar system suggests that a merger of this kind took place within the vicinity of the solar system shortly (a few hundred million years) before its formation.

I. INTRODUCTION

Rapid neutron capture (“r-process”) has been known as a basic formation process for the heaviest elements in the cosmos since the seminal work of BBFH [2] and Cameron [3]. The question in which astrophysical environment it actually occurs, however, has puzzled astrophysics ever since. Traditionally, core-collapse supernovae have been considered as the favored production site [4–8], see [9] for a recent review. As an alternative site, Lattimer and Schramm [10] suggested the decompression of cold nuclear matter ejected during the tidal disruption of a neutron star by a stellar mass black hole, a process that occurs in a similar way during the merger of two neutron stars.

Eichler et al. [1] placed compact binary mergers (CBMs) in a broader astrophysical context. They suggested that in addition to bursts of gravitational waves and neutrinos CBMs are the engines of a subclass of Gamma-ray Bursts (GRBs). Estimating the rate of mergers they also suggested that these events could be a major source of r-process material. In the first detailed calculation of mass ejection from a merger, Rosswog et al. [11] found that ∼ 10−2 m⊙ become unbound during a merger event due to gravitational torques and hydrodynamic interaction (this is referred to as “dynamic ejecta” in the following). In their follow-up work [12] they performed the first network calculations based hydrodynamics simulations which showed that the resulting abundance patterns agree well with the observed solar system abundances for A > 130 and, folding the ejecta masses with the estimated merger rates, this indicated that, indeed, CBMs could represent a major source of cosmic r-process. At the same time Li and Paczynski [13] suggested that the radioactive decay of the neutron-rich nuclei in these “dynamic ejecta” would produce a macronova (also referred to as kilonova): a short lived optical - IR weak supernova-like signal. The suggested triple link between GRBs, heavy element nucleosynthesis and macronovae will be the backbone of this paper.

During the past decade much effort has been invested in understanding the relevance and the implications of CBM r-process. [13–35]. The picture that emerges from this wealth of studies is the following: a) the dynamic ejecta with their extreme neutron-richness provide excellent conditions for heavy (A > 130) r-process and the resulting abundance pattern is largely independent of the specifics of the merging binary system [e.g. 24] and b) CBMs provide additional nucleosynthesis channels such as neutrino-driven winds and the final dissolution of the accretion disk which likely complement the nucleosynthesis from the dynamic ejecta [e.g. 36].

On the other hand, essentially all recent studies agree that the originally favored scenario, core-collapse supernovae, is seriously challenged, at the very least for the production of elements heavier than A = 110 [9, 37–43]. (An exception may possibly be very rapidly rotating, highly magnetized progenitor stars that can also produce favorable conditions for r-process [45].) Despite the growing consistency among different theory/simulation results – in favour of CBMs, against core-collapse supernovae – some reservations against the neutron star merger scenario have remained, mainly due to the unsettled question whether or not they are consistent with the chemical evolution of galaxies [46–48].

Studies of macronova evolution [13, 30, 49, 53] revealed its prospects for detectability. Most notable is the recent realization [29] that the opacity of the ejecta will be fairly...
large as it will be dominated by Lanthanides. This has lead to a qualitative shift in the expected light curve. While earlier estimates, based on iron group opacities, predicted a UV-optical signal at around half a day [13 49–51], recent ones used opacities of Lanthanides and obtained a weaker IR signal peaking at a week [39 52 53]. On June 3rd 2013 the Swift satellite detected a relatively nearby sGRB [54] at a redshift of 0.356. With a duration of 0.18 ± 0.02s and with a hard spectrum GRB 130603B is a genuine non-collapsar [55]. It had a regular optical and X-ray afterglow with some X-ray excess at > 1 day [56], perhaps indicating a fallback accretion [57]. Later radio afterglow observations suggested a jet break [58]. At 9 days after the burst (≈ 6.6 days in the local rest frame) HST [58 59] detected a nIR point source with an apparent magnitude of H_{160, AB} = 25.73 ± 0.2 (M_{L, AB} ≈ −15.35), corresponding to an intrinsic luminosity of ≈ 10^{41} erg/sec. The upper limit on the IR band emission at the same time, R_{606, AB} > 28.5, suggests that the regular afterglow has decayed by this time. The IR excess at 9 days after the burst was interpreted by both groups as tentative evidence for a Li-Paczynski macronova. In the following we consider the implications of this interpretation for the r-process nucleosynthesis. If this interpretation is correct it has several interesting implications. It provides the first direct evidence that sGRBs arise from CBMs. Furthermore, within the macronova model the IR emission arises from the combination of the heating of the neutron star debris via radioactive decays [13] and the large opacity dominated by Lanthanides [29]. Thus, the observations indicate that (i) CBMs indeed power sGRBs and (ii) they are also the sources of a substantial fraction of the heaviest r-process nuclei. This provides the impetus to revisit the role of compact binary mergers for the formation of the heaviest elements in the Universe.

In the following we derive limits on the amount of ejected material in §2. In §3 we discuss the implications for cosmochronology, in §4 the implication to the composition of the early solar system and in §5 those for the CBMs.

II. LIMITS ON THE EJECTED MASS

The nIR luminosity and the late time heating rate [61] yield a lower limit on the ejected mass:

\[ m_{ej} > 0.02 (\epsilon/0.5)^{-1} m_\odot, \]

where \( \epsilon \) is the fraction of radioactive energy in electrons or positrons and \( \gamma \)-rays. We assume conservatively that this fraction is converted locally to heat and radiated as nIR. While conservative this strict lower limit is in rough agreement with various estimates of the macronova light curve [30 52 53]. It is subject only to uncertainties in the estimates of the radioactive heating rate and of the fraction of energy that is captured and re-emitted. At the maximum only about half of the mass contributes to the emission, therefore we use in the following 0.04 m_\odot as an estimate for the ejected mass.

The radiation escape condition is \( m_{ej} \kappa_L / (4\pi (v_{ej} t)^2) \approx \epsilon/v \), where \( \kappa_L \) is the opacity and \( v \) is the typical velocity of the ejected material. This yields \( v_{ej} = 0.2 \epsilon (m_{ej} / 0.04 m_\odot) \) and a size of \( 3 \cdot 10^{15} (m_{ej} / 0.04 m_\odot) \) cm. The corresponding black body temperature \( \sim 1500 K \) with a peak emission at \( \sim 2 \mu M \), is consistent with the observed nIR peak. The peak time would have been at approximately 4.5\((m_{ej} / 0.04 m_\odot)^{1/2}(\kappa_L / 10 gm/cm^2)^{1/2}(\epsilon/0.2\epsilon)^{-1/2}\) days, suggesting a lucky coincidence in the choice of the observing epoch.

III. R-PROCESS NUCLEOSYNTHESIS

Assuming solar-system abundances [65] everywhere the Milky Way contains \( M_{A>130} = 1.6 \cdot 10^4 \) m_\odot in “heavy” (\( A > 130 \)) r-process material. We assume that a) all mergers eject a comparable amount of r-process material to the one observed in this event and b) only CBMs are responsible for the heavy r-process. With \( m_{ej} = 0.04 m_\odot \)

\[ N = 4 \cdot 10^5 \left( \frac{M_{A>130}}{1.6 \cdot 10^4 m_\odot} \right) \left( \frac{0.04 m_\odot}{m_{ej}} \right) \]

mergers should have taken place in the Galaxy. The corresponding merger rate,

\[ R_{CBM} = 300 \left( \frac{0.04 m_\odot}{m_{ej}} \right) \left( \frac{M_{A>130}}{1.6 \cdot 10^4 m_\odot} \right) Gpc^{-3} yr^{-1} \]

should be compared with the sGRB rate [66] \( R_{sGRB} = 6 \pm 2 \) Gpc\(^{-3}\)yr\(^{-1}\) which agrees within a factor of 2 with various previous estimates [62 63 67] (which is inversely proportional to a lower sGRB luminosity limit, here taken as 5 \cdot 10^{49} erg/s, roughly the lower value of luminosity for all sGRBs with known redshifts). This implies that only 1 out of 50 mergers produces an observable sGRB, which could arise either from some mergers failing to produce a detectable burst or from a finite beaming angle. The latter is consistent with the estimated beaming correction of \( \sim 100 \) for this burst [56], but this number is not very well constrained. Estimates based on the observed binary pulsars in the Galaxy are highly uncertain, with values in the range \( R_{pulsars} = 20-20000 \) Gpc\(^{-3}\)yr\(^{-1}\) [65 72] and a canonical value of \( \approx 800 \) Gpc\(^{-3}\)yr\(^{-1}\). These values are consistent with the above rates.

Turning now to cosmochronological evolution we note that there exists an observed correlation between abundances of r-process elements and Fe at [Fe/H] > -2.5 [73 75]. Since Fe enrichment is controlled by type Ia SNe occurring at a much higher rate, widely varying degrees of mixing of the r-process ejecta in an already existing merger
remnant with Fe produced by fresh SNe would result in large scatter in the r-process abundances over a broad range of [Fe/H].

By comparison with supernovae Qian [40] argued that the dynamic ejecta from a single event cannot mix with more than $m_{\text{mix}} \approx 3 \times 10^4 m_\odot$ material. If the ejecta are all r-process this would lead to a fraction of $3 \times 10^{-7} (m_{\text{ej}}/0.01 m_\odot)(3 \times 10^4 m_\odot/m_{\text{mix}})$ which, as he argues, would strongly disfavor neutron star mergers since this fraction is much larger than observed. Furthermore, as one expects only about $5 \times 10^5$ mergers in the Galaxy and there are about $10^7$ “cells” of $3 \times 10^4 m_\odot$ not all material would be mixed with r-process products. Argast et al. [47] carried out a detailed simulation and reached the same conclusion on the basis of similar ideas.

We argue here that substantial mixing could resolve this problem. This could arise simply due to galactic rotation, which leads to significant mixing on a rotational time scale of $\sim 200$ Myr, due to Rosetta-type or volume-filling orbits of stars/debris, not uncommon in a typical galaxy, and due to turbulent diffusion. For the latter, with a typical turbulent velocity $v_{\text{turb}} \approx c_s \approx 10^8$ cm/s one expects significant mixing on a $\sim 200$ Myr time scale. This depends critically on the size of the turbulent cells. We have conservatively assumed a size of 1 pc. Diffusion will be much more effective, like the square root of this quantity, if these cells are larger. At early times galaxies were more turbulent and [76] observe turbulent motion of up to $150$ km/sec in milky way like galaxies at $z \sim 2$, with a corresponding diffusion length of a kpc. This could easily lead to significant mixing within one or two rotations. Finally, if the neutron stars in compact binary systems receive, like single neutron stars, a kick at birth, they may travel a few kpc out of the midplane [see e.g. [77-80], consistent with the observation of the locations of sGRBs [81]. This would mean that the ejecta are sprayed over a larger volume and can easily mix with a substantially larger amount of mass.

Thus a uniform distribution of r-process material can be established. The observations of a large scatter in [Eu/Fe] abundances at low metallicity stars are consistent with this picture in which heavy r-process material is produced in rare events and in large amounts. At early times some material was exposed to such events while other material was not.

Abundances of r-process elements have been observed in halo and disk stars covering a metallicity range [Fe/H] $\approx -3.1 - 0.5$ [82-87]. This requires a significant fraction of r-process nucleosynthesis to take place within a few Myr. Some population synthesis models [88] suggest such a rapid population of mergers. However, this requirement is in a direct contrast with estimates of the time delay between sGRBs and the SFR [e.g. 66]. Typical delays are found by all groups to be of order of 3 Gyr. The distribution around this time delay is rather narrow, not larger than 1.5 Gyr.

Can one resolve this inconsistency? The in-spiral time is very sensitive to the initial orbital period and eccentricity. For typical ns$^2$ parameters a modest variation by a factor of 7 in the initial separation (from $2 \times 10^{11}$ cm to $3\times 10^{10}$ cm would change the merger time all the way from 3 Gyr to 1 Myr, which is practically instantaneous. Even the larger separations, that correspond to long merger times of several Gyr are significantly smaller than the two original stellar radii. This implies that the system must have undergone a common envelope phase and the initial separation of the binary (and hence the merger time delay) depends critically on this poorly understood phase. Most observed sGRBs are at relatively low redshifts. Conditions could have been different at earlier epochs, where low metallicity may have lead to shorter delays. Note that such low metallicity systems could have arisen without contamination by the SNe that formed the neutron stars as some neutron stars (e.g. J0737-3039B) formed in a collapse with practically no mass ejection [43]. Alternatively it is possible that a second channel of special rare type of SNe [45], that can operate only at very early times, produces the earliest $A > 130$ material. However, as these SNe require very fast rotation and hence can operate only in low metallicity stars, they are unlikely to produce the bulk of the r-process material.

IV. IMPLICATIONS TO THE EARLY SOLAR SYSTEM

Evidence for $^{244}$Pu, with a half life time $t_{1/2} = 81$ Myr ($\tau = 117$ Myr) in the Early Solar System [89] provides further independent evidence for the rarity of formation episodes of r-process material. This shows actinide production in the vicinity (in time and space) of the Solar System prior to its formation. However, searches [90, 91] for traces of $^{244}$Pu isotope in deep-sea crust and sediment accumulated over the last $\sim 25$ Myr have found none. The current limits on deep-sea crust and sediments are that the $^{244}$Pu abundance is lower by a factor 30-200 than expected from a uniform production model, assuming actinide production in SNe and reasonable assumptions on interstellar ISM deposition. These findings suggest that: (a) formation of $^{244}$Pu and heavy r-process in general occurred in rare episodes such as CBMs, and (b) one of CBMs took place in the vicinity of our early Solar system less than a few hundred million years just prior to its formation.

V. IMPLICATION TO COMPACT BINARY MERGERS

The derived lower limit on $m_{\text{ej}}$ is consistent with the models of [30] and [52]. But at least if we take all current numbers at their face values, this would make a double neutron star merger as somewhat unlikely “engine” for this sGRB and the subsequent macronova emission. Different groups find the following numbers from numerical simulations: $m_{\text{ej}} < 0.04 m_\odot$, [52]; $m_{\text{ej}} < 0.02 m_\odot$, [52].
process material becomes rather uniform at a rather early stage. They also indicate early deposition of such material. The observed uniformity can be obtained if mixing within the galaxy is rapid enough. This is plausibly mediated by turbulent mixing, differential rotation, and the fast motion of some binaries within the Galaxy. One has to recall that the early galaxy was much more erratic than the Milky Way we observe today and that turbulent velocities of 150 km/sec have been observed in z ~ 2 galaxies. The various mechanisms could easily mix the galaxy over a few rotational periods.

The CBM r-process model requires rapid mergers took place at a very early stage. Such a population of rapid merger has been suggested by population synthesis [88]. However, the observed redshift distribution and luminosities of sGRBs suggest a typical spiraling-in time of 2-3 Gyr. A possible way to reconcile the two observations is that an earlier stellar population (e.g. of low metallicity) had somewhat lower initial separations. The required change in the initial separation is only moderate. Alternatively it is possible that the earliest r-process material is produced via another channel [43].

It is interesting to note that evidence for $^{244}$Pu in the Early Solar System [89] and with lack of evidence for deposition of this isotope from the ISM during the last 25 Myr [90] suggest that this isotope, as well as other heavy r-process elements are produced in rare episodes. If heavy r-process material is indeed produced in CMBs this implies that such an event took place in the vicinity of the solar system just prior to its formation.

To conclude we note that the idea that the recently observed GRB130603B with a macronova was accompanied by a significant mass ejection could possibly be tested if the surrounding density is not too low (current estimates are $\sim 5 \cdot 10^{-3} - 30$ cm$^{-3}$, [50]). In such a case we expect a significant (a few tens of $\mu$Jy) radio signal to arise from the interaction of this ejecta with the circum-merger matter [51]. This signal would rise on a time scale of months or a year and should be detectable by the Expanded Very Large Array (EVLA). A detection would be a direct confirmation. However, even if for some reason (e.g. low circum-merger density) this signal should not be detectable we can expect a detection of another sGRB at a comparable distance within a year or two. This scenario has a clear prediction and the identification of the accompanying IR macronova is expected.

VI. CONCLUSIONS

The tentative identification of a macronova following a sGRB has numerous far-reaching implications. It provides a direct proof that sGRBs arise from compact binary mergers, as [1] suggested long ago. The late IR signal clearly indicates high-A material and demonstrates that these events are associated with the production of r-process material. The assertion that they are indeed the sources of most of the heavy r-process material has additional implications. It narrows down both the mass ejection from these sources as well as their rate and cosmic evolution. (i) The lower limit on implied mass $m_{ej} > 0.02m_\odot$, which is only subject to errors in the estimated radioactive heating rate is at the very high end of ns$^2$ mergers [see e.g. 32, 51]. Together with the large estimated ejecta velocity, this points to the involvement of a black hole, either in a merger or in a dynamical collision [31]. (ii) The required rate is consistent with sGRB rate estimates with a reasonable beaming factor of order 50. This is consistent with current estimates of beaming of sGRBs [50]. Favorable indications towards this idea include: (a) uniformity in abundances, suggesting a regular source - freely expanding neutron star material is natural (b) problems with SNe nucleosynthesis (c) large fluctuation at early times - indicating a rare process that produces a significant amount of material at each episode. In the past arguments against compact binary mergers as sources of r-process material have been mostly based on indications from chemical evolution of the Galaxy. Observations suggest that the distribution of heavy r-process material becomes rather uniform at a rather early stage. The observed uniformity can be obtained if mixing within the galaxy is rapid enough. This is plausibly mediated by turbulent mixing, differential rotation, and the fast motion of some binaries within the Galaxy. One has to recall that the early galaxy was much more erratic than the Milky Way we observe today and that turbulent velocities of 150 km/sec have been observed in $z \sim 2$ galaxies. The various mechanisms could easily mix the galaxy over a few rotational periods.

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