On the role of GRBs on life extinction in the Universe

Tsvi Piran\textsuperscript{1} and Raul Jimenez\textsuperscript{2,3,}\textsuperscript{*}

\textsuperscript{1}Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel
\textsuperscript{2}ICREA & ICC, University of Barcelona, Marti i Franques 1, Barcelona 08028, Spain.
\textsuperscript{3}Institute for Applied Computational Science, Harvard University, MA 02138, USA.

(Dated: November 14, 2014)

As a copious source of gamma-rays, a nearby Galactic Gamma-Ray Burst (GRB) can be a threat to life. Using recent determinations of the rate of GRBs, their luminosity function and properties of their host galaxies, we estimate the probability that a life-threatening (lethal) GRB would take place. Amongst the different kinds of GRBs, long ones are most dangerous. There is a very good chance (but no certainty) that at least one lethal GRB took place during the past 5 Gyr close enough to Earth as to significantly damage life. There is a 50% chance that such a lethal GRB took place during the last 500 Myr causing one of the major mass extinction events. Assuming that a similar level of radiation would be lethal to life on other exoplanets hosting life, we explore the potential effects of GRBs to life elsewhere in the Galaxy and the Universe. We find that the probability of a lethal GRB is much larger in the inner Milky Way (95% within a radius of 4 kpc from the galactic center), making it inhospitable to life. Only at the outskirts of the Milky Way, at more than 10 kpc from the galactic center, this probability drops below 50%. When considering the Universe as a whole, the safest environments for life (similar to the one on Earth) are the lowest density regions in the outskirts of large galaxies and life can exist in only \(\approx 10\%\) of galaxies. Remarkably, a cosmological constant is essential for such systems to exist. Furthermore, because of both the higher GRB rate and galaxies being smaller, life as it exists on Earth could not take place at \(z > 0.5\). Early life forms must have been much more resilient to radiation.

INTRODUCTION

Gamma Ray bursts (GRBs), short and intense bursts of \(\gamma\)-rays, are the brightest explosions known. The copious flux of \(\gamma\)-ray photons with energies above 100keV from a galactic GRB could destroy the ozone layer making them potentially damaging to life on Earth. This has led to the suggestion\textsuperscript{[1]}\textsuperscript{2}\textsuperscript{10} that events of massive life extinction were caused by galactic GRBs. This issue depends on course on the rate of galactic GRBs in the Earth neighborhood. Once it was realized that long GRBs are preferentially located at low-metallicity environments it was claimed\textsuperscript{[11]} that nearby Galactic GRB are rare and GRBs are unlikely to play any role in life extinction on Earth (see however,\textsuperscript{[12]} who claims that metallicity won't protect life on Earth from GRBs). Given the recent significant progress in quantifying the main ingredients that determine whether GRBs have any effect on Earth: their rate, luminosity function and dependence on metallicity it is therefore timely to re-assess this issue, extending the discussion to GRBs effects on life in the whole Milky Way and in the whole Universe.

GRBs are traditionally divided in two groups according to their duration: long (\(>2s\)) GRBs (LGRBs) and short (\(<2s\)) GRBs (sGRBs). This division follows to a large extent the origin of these events. LGRBs are associated with the death of massive stars [see e.g.\textsuperscript{[14]} for a review] while sGRBs have a different origin, most likely compact binary mergers\textsuperscript{[15]}. Recently, it was realized that there is a third group characterized by low luminosity (\(L \approx 10^{46-48}\) erg s\(^{-1}\)) and denoted sLGRBs. These events are also associated with the death of massive stars, but they originate from a different physical mechanism\textsuperscript{[13]}. A fourth type of a related explosion - giant SGR flares might also relevant. Such a flare took place in the Milky Way on 27 Dec 2004, releasing \(\approx 4 \times 10^{46}\) ergs\textsuperscript{[17]}. This flare, that was sufficiently powerful to disturb the Earth ionosphere, seen as a brief change in the ionization levels in the lowest regions of the Earth’s ionosphere (the D-layer), is the only known object outside the solar system to have a direct clear impact on Earth. In fact, this type of disturbance was first seen from a GRB880301 in 1983\textsuperscript{[18]}\textsuperscript{[19]}\textsuperscript{[20]}\textsuperscript{[21]}. Giant SGR flares are a different phenomenon than GRBs but as their rates could be as high as once per thirty years in the Galaxy, we explore their possible role as well. Solar flares are another potential life threatening source as they are stronger than previously thought\textsuperscript{[19]–\textsuperscript{21]}.

Wanderman and Piran\textsuperscript{[22]} have recently reconstructed, in a model independent way, the rate of LGRBs as a function of redshift and their luminosity function. One of their most interesting findings is that the LGRB rate is not reproduced by the star formation rate of the global galaxy population. This discrepancy is statistically highly significant, particularly at low (\(<3\)) red-
shifts, which is relevant here. This is, at first, surprising as there is ample evidence that long duration GRBs originate from the collapse of very massive stars and one would expect that LGRB follow the SFR. Jimenez & Piran [23] have shown that the LGRB rate and the galaxy derived star formation rate (SFR) agree for a special class of galaxies: low mass (stellar mass $< 10^{10} \, M_{\odot}$) and low metallicity ($\lesssim 1/10$ solar). This is, of course, done in a statistical sense and does not exclude that few outliers to this trend exist. But it is clear that the LGRB host population is a special subclass of the general galaxy population. These results are in agreement with earlier observations that indicate that LGRBs take place in dwarf [24], low metallicity [25] galaxies. They are also consistent with direct observations of LGRBs host metallicities [e.g. 26 28] and with the findings of Fruchter et al. [29] who have shown that the local SFR in the vicinity of LGRBs is much higher than expected if they simply follow the general SFR of the host galaxy [see also 30].

sGRBs have very different host environments and they clearly arise from different progenitors [see e.g. 31 32 for reviews]. They are significantly weaker than LGRBs and as such are observed to much shorter distances than LGRB, sGRBs are believed to originate in compact binary mergers [15] but a direct proof for that is still lacking. As sGRBs are weaker, fewer GRBs have been observed than LGRBs. However their current overall rate is about five times larger than the rate of LGRBs. In the following we use a recent determination of the sGRBs global rate and luminosity function by Wanderman & Piran [33].

LGRBs are significantly weaker with energies of $10^{47–49}$ erg (as well as smoother and softer) than both LGRBs and sGRBs. Like LGRBs they are associated with the death of massive stars but they arise due to a different physical mechanism [16]. While less than half a dozen LGRBs have been observed so far they are more numerous than both LGRBs or sGRBs [34]. Because of their low luminosities they are observed only up to relatively short (but still cosmological) distances.

We use the very recent determination of GRB rates and luminosity function to estimate the flux of Galactic GRBs on Earth and compare it with the flux needed to destroy the ozone layer. Given that LGRBs are the most powerful and hence most dangerous, and given their dependence on metallicity we begin with an exposition of the Milky Way metallicity distribution. We continue estimating the life threatening effect of LGRBs, turning later, using the same formalism to sGRBs, LGRBs and giant SGR flares. We conclude summarizing the results and their implication to life extinction on Earth. We also explore the implications to life extinction on exoplanets elsewhere in the Milky Way and in the whole Universe.
hosts with direct metallicity determinations (dashed blue lines) as compiled by [26] and those of GRB hosts metallicities derived from DLA measurements (red line) as reported by [28]. The percentage of overlap of direct hosts metallicities with those of stars in the Milky Way is 10%. We conclude that the metallicity bias will reduce the probability for LGRB within the last 5 Gyr in the Milky Way by a percentage between 5% (from the metallicity determination by [23]) and 10% (from direct metallicity determinations [e.g. 26, 28]), resulting in a reduction factor between 10 and 20 as compared to the volumetric rate of LGRBs. In what follows we will assume a conservative 10% value for a metallicity bias for LGRB above solar.

LIFE THREATENING GRBS IN THE MILKY WAY

Following Wanderman & Piran [22, 33] we write the current (\(z = 0\)) luminosity function as:

\[
\phi(L) = n_0 \begin{cases} 
(L/L^\ast)^{-\hat{\alpha}} & L_{\text{min}} < L < L^\ast \\
(L/L^\ast)^{-\beta} & L^\ast < L < L_{\text{max}}.
\end{cases}
\]  

(1)

The parameters of the luminosity functions\(^3\) are given in Table I and the functions are shown in Fig. 2. This luminosity and rate are the isotropic equivalent (namely dispersed by beaming), which are the quantities needed for our estimates here. In the following we need the total energy (see also Ref. [37]) and not the peak luminosity. A good but rough estimate is obtained by assuming a typical duration of 20s (1s) for LGRBs (sGRBs). Multiplying by the average (~ half) of the peak flux we obtain \(E_{\text{LGRB}} = 10L\) and \(E_{\text{sGRB}} = 0.5L\). In what follows we adopt the cosmological volume occupied by a Milky Way type galaxy as \(10^{-7}\) Gpc\(^3\) (see e.g. Panter et al. [38] Fig. 3 where we use \(6 \times 10^{10}\) M\(_\odot\) as the stellar mass of the Milky Way [39]).

Assuming that GRBs follow the stellar distribution, they are distributed in the exponential disk of the Milky Way with a radial density profile given by \(\rho \propto \exp(-r/r_d)\), with \(r_d = 2.15 \pm 0.14\) kpc (a number that, surprisingly, has only been accurately determined recently [40]). Using this density profile we calculate \(p(d, R)\), the fraction of the Galaxy within a distance \(d\) from a position \(R\) (see Fig. 3). The expected number of GRBs, with a fluence exceeding \(F\) at a location at distance \(R\) from the Galactic center is:

\[
\langle N \rangle = \int_{L_{\text{min}}}^{L_{\text{max}}} \phi(L) p(d(E, F), R) dL.
\]  

(2)

To estimate the effect of a GRB on life on Earth we need to know what the dangerous radiation doses are. Ruderman [1], who considered at the time the effect of a nearby SNe on Earth, realized that the most damaging effect would be the depletion of the Earth protective Ozone layer for a period of months. This would happen via formation of stratospheric nitric oxide that destroys the Ozone. The Ozone depletion would lead to enhancement of UVB solar radiation that, in turn, would be harmful to life. Note that the UVB fluence on the surface of the ocean will destroy surface marine life [as described in detail in Ref. 8 among them plankton, which will deprive (marine) life of their main nutrient. In 1995, after it was realized that GRBs are cosmological and their rate was estimated, Thorsett [2] applied these ideas to Galactic GRBs. A decade later Thomas et al. [7] carried out the most extensive, to date, calculation of the effects of the gamma-ray flux on the Earth atmosphere. They find that a fluence of 10kJ/m\(^2\) will cause a depletion of -68% of the ozone layer on a time scale of a month. Fluxes of 100kJ/m\(^2\) and 1000kJ/m\(^2\) will cause depletions of -91% and -98% respectively. One has to realize that these are average quantities. The exact amount of depletion depends on the direction of the GRB as well as on the season when the GRB takes place and may vary from one latitude to another. Following Thomas et al. [7] we estimate that a fluence of 10kJ/m\(^2\) will cause some damage to life, while 1000kJ/m\(^2\) will wipe out nearly the whole atmosphere causing a catastrophic life extinction event; we consider \(F = 100kJ/m^2\) as our canonical life threatening fluence. We don’t consider here other sources of damage, such as the possibility that cosmic rays (CR) are associated with the GRBs and those could lead to enhanced radioactivity in the atmosphere [3, 4]. The mean free path for deflection in the galactic magnetic field for a 100 GeV proton is 1 kpc. So the lowest part of the CR spectrum which contains the largest number of CRs will be deflected and won’t reach Earth if the event is more than 1 kpc away. This also means that while we will get eventually CR flux from GRBs that don’t point towards Earth, a single event will always be less powerful (because of deflection away of CRs) so their effect will be weakened and depending on their spectrum significantly weakened.

Integrating over the luminosity functions in eq. 2 we estimate \(\langle N \rangle\), for both long and short GRBs. These values are listed in Table II. To estimate the significance of these numbers taking into account the errors in the luminosity function, burst duration and the Milky Way disk scale length, we carry out a Monte Carlo simulation of 1000 realizations for both long and short GRBs. We calculate the distribution of \(\langle N \rangle\) and the overall probability of more than one life threatening GRB taking place within the last 5 Gyr, 1 Gyr and 500 Myr.

Inspection of Fig. 2 reveals that maximal danger arises from \(\sim L^\ast\) bursts. Lower luminosity bursts are more

---

\(^3\) The luminosity function defined here, \(\phi(L)\), is per \(dL/L^\ast\). As such it differs from that given in [22, 33] that is per \(d\log_{10}(L)\). The power law indices are marked by \(\hat{\alpha}\) to denote this difference. Clearly, \(\hat{\alpha} = \alpha + 1\) and \(\hat{\beta} = \beta + 1\).
TABLE I. Parameters of the LGRBs and sGRBs luminosity functions from Wanderman & Piran [22, 33]. Note that the upper and lower limits are not well determined but this is unimportant for our estimates here.

|       | \(n_0\)  | \(\hat{\alpha}\) | \(\hat{\beta}\) | \(L^*\)   | \(L_{\text{min}}\) | \(L_{\text{max}}\) |
|-------|----------|-----------------|---------------|----------|-----------------|-----------------|
| LGRB  | \(0.15^{+0.08}_{-0.08}\) | \(1.2^{+0.2}_{-0.1}\) | \(2.4^{+0.3}_{-0.6}\) | \(10^{52.5} \pm 0.2\) | \(10^{49}\) | \(10^{54}\) |
| sGRB  | \(0.04^{+0.023}_{-0.019}\) | \(1.9 \pm 0.12\) | \(3.0^{+0.1}_{-0.8}\) | \(10^{52.3} \pm 0.2\) | \(5 \times 10^{49}\) | \(10^{53}\) |

FIG. 2. Left y-axis: the mass fraction of the galaxy from which the fluence on a planet will exceed 100 kJ/m\(^2\) for a given explosion energy (x-axis). The colored curves correspond to different locations of the life harboring exoplanet (2.15, 4.85, and 16 kpc from the Galactic center). We have adopted for the MW an exponential disc with scale-length of 2.15 kpc. The right y-axis provides (for the gray curves) the number of GRBs in the MW in the past 5 Gyr per erg. For a given energy, the product of the corresponding colored and gray curves gives the number of damaging GRBs to life per energy interval.

abundant but their covering fraction of the Galaxy is too small. Higher luminosity bursts can destroy life on a large fraction of the Galaxy but those are extremely rare. From the point of view of computational certainty these results are reassuring as the confidence in our determination of the rate of events around \(L^*\) is good. This is also important from another point of view. Spatially GRBs are concentrated within regions of the highest SFR [29, 30]. The dominance of strong GRBs whose radius of influence is a few kpc implies that we can ignore this spatial inhomogeneity and the approximation that the distribution of LGRBs follow the distribution of matter in the galaxy holds.

We find that the probability of a LGRB, in the past 5 Gyr, with fluence 100kJ/m\(^2\) on Earth to be higher than 90% and in the last 0.5 Gyr this probability is 50%. It is somewhat surprising that this result (50% chance of a biospherically important event in a half Gyr) is so similar to the original calculation in Thorsett [2]. At lower fluence, 10kJ/m\(^2\), these probabilities are higher than 99.8% (95%) for 5 Gyr (0.5 Gyr) and thus nearly certain. However, the chances of a truly catastrophic event with a fluence of 1000kJ/m\(^2\), are at most 25% thus making it unlikely. These probabilities are of course much larger (see Table. II) if we ignore suppression of GRBs in the Milky Way due to large metallicity.

sGRBs are weaker and as such, even though their rate
is larger than the rate of LGRBs (and particularly so in the Milky way, because of the metallicity bias) their life threatening effect is negligible as can be seen from Table II. As lGRBs are even weaker their effect is completely negligible. For completeness we mention that a giant SGR flare would have to be within $\sim 1 - 2$ pc from Earth to produce a 100kJ/m$^2$ fluence. This is comparable to the distances between stars in the solar neighbourhood. Consequently giant SGR flares are unlikely to cause any significant damage to life.

FIG. 4. The probability, $P(\langle N \rangle)$, of having on average more than one lethal GRB in the past Gyr for an exoplanet at a distance $r$ from the centre of the Milky Way. The grey line shows the fraction of mass in the Milky encompassed within a radius $r$. The dashed line is for LGRB assuming no metallicity correction.

TABLE II. Probability, in %, of at least one GRB having occurred in the past time $t$ with enough flux to produce significant life extinction. For LGRB we show without parenthesis the probability when there is a 10% metallicity bias, in parenthesis when there is none. We consider three cases of the GRB fluence on Earth (10, 100 and 1000 kJ/m$^2$).

| t < 5 Gyr | t < 1 Gyr | t < 0.5 Gyr |
|----------|----------|------------|
| LGRBs    | 99.8 (99.95) | 98.7 (99.90) | 95 (99.80) |
| sGRBs    | 80        | 37         | 22         |
| lGRBs    | < 1       | < 1        | < 1        |

| 100kJ/m$^2$ |
|-------------|
| LGRBs       | 90 (99.8) | 60 (96) | 50 (90) |
| sGRBs       | 14        | 3       | 2       |
| lGRBs       | < 1       | < 1     | < 1     |

| 1000kJ/m$^2$ |
|--------------|
| LGRBs        | 25 (80)  | 7 (40)  | 4 (25)  |
| sGRBs        | $10^{-2}$| $2 \times 10^{-3}$| $10^{-3}$|
| lGRBs        | 0        | 0       | 0       |

GRBS AND LIFE IN THE GALAXY

We turn now to explore the possible threat caused by GRBs to life elsewhere in the Milky Way, turning to the whole Universe in the next section. Clearly to do so one must assume the lethal radiation dose that will be threatening to life elsewhere. While life can take numerous other forms and could be much more resilient to radiation than on earth, we make here the conservative assumption that life is rather similar to the one on Earth. This common assumption is the basis for searches of Earth like exoplanets as places that harbour life. Under this assumption, we explore what is the likelihood that a nearby exoplanet results in a dose of 100 as well as 10 and 1000 kJ/m$^2$ in various regions of the Milky Way.

The stellar density is significantly larger towards the center of the Galaxy and hence the threat to life on most exoplanets, that reside in this region, is much larger. Fig. 4 depicts the probability of having one life threatening event within the last 4 Gyr as a function of the distance $r$ of an exoplanet from the Galactic center. Also shown is the fraction of the stellar population of the Milky Way within this radius. A lethal GRBs of 100kJ/m$^2$ would be more likely than 95% up to a distance of 2 kpc from the Galactic center in which 25% of the MW stars reside. When considering $F = 10$ and 1000kJ/m$^2$ we find 12 and 0.5 kpc respectively. In agreement with the specific estimates for Earth, events around the Solar distance from the Galactic could be significant but rare and only at a distance $> 10$ kpc the threat from GRBs becomes small. Therefore, life can be preserved with certainty only in the outskirts of our Galaxy. In total 90, 40 and 5% of the exoplanets in the MW would be exposed to a fluence of 10, 100, and 1000 kJ/m$^2$ from GRBs within a period of 1 Gyr.

Finally, given the LGRBs luminosity function there are practically no lethal events with a distance larger than 30kpc. This implies that nearby small satellite galaxies with a large SFR, like the LMC, are too far to influence life in the Milky Way. The fact that the local group is such a low density region containing only two large galaxies (Andromeda and the Milky Way) and with the nearest cluster of galaxies, Virgo, at 16 Mpc, i.e. much farther away than the typical inter-galactic distance of 1 Mpc, seems to provide the required environment to preserve life on Earth. There is no threat from nearby extragalactic bursts.

4 We use 1 Gyr as a round number to estimate life extinctions that could have cause a massive extinction that terminated life and thus made it unlikely that we find signs of life today.
Before concluding we turn now to consider the conditions elsewhere in the Universe. We already mentioned that the local neighbourhood of the Milky Way has a lower density of star forming dwarf galaxies making the Milky Way a more friendly neighbourhood for life. We can take our calculation one step further and compute the effective volume in the Universe protected from GRB explosions for life proliferation. This happens for galaxies that produce enough metals so that their metallicity is at least 1/3 solar and their stellar disks are larger than 4 kpc. Using the mass-metallicity relation in Panter et al. [36] their Fig. 6] such galaxies must have stellar masses larger than $10^{10} M_\odot$. This corresponds to a co-moving abundance of $10^{-3}$ galaxies per Mpc$^3$ (see Fig. 3 of Panter et al. [35]). This is a factor 10 less than the abundance of most common galaxies. Galaxies friendly to harbor and preserve life will preferably inhabit low density regions in voids and filaments of the cosmic web.

Turning to earlier epochs we may wonder whether life could have existed in the earlier universe? We recall that the age of the Universe at $z=1$ is about 6 Gyr so in principle there was enough time for life to evolve even before this redshift; here we note that the LGRB rate is significantly larger in the past making the GRB threat much more significant. Furthermore, galaxies at high-$z$ are smaller than current ones by a factor of 2 – 4 in radius and as such have less room for isolated safe regions like the outskirts of the Milky Way. We conclude that it is impossible to harbor life at $z > 0.5$ as LGRBs will always be sufficiently nearby to life-harboring planets and thus cause life extinctions. It seems the survival of life, as we know it on Earth, was only a recent phenomenon in the history of the Universe caused by the growth of large galaxies. Life forms that might have existed earlier or that exist today in other regions of the Universe that are much more susceptible to significant GRB bombardment must have been much more resilient to radiation than life on Earth. Of course we do not know whether destruction of a large fraction of life and life forms on a given planet is good or bad for the long-term evolution of higher life-forms on that planet, only that it would be highly damaging for the existing higher life forms, including humans, on our own planet right now, and this is what this study in essence concerns.

CONCLUSIONS

We have used the latest determination of GRB rates and luminosities to estimate the likelihood of them being the source of life extinction on Earth. Using also the latest determinations of metallicity of stars in the Milky Way and those of LGRB hosts, we concluded that the likelihood of a GRB producing life extinction on Earth is high. Taking the same lethal dose for extraterrestrial life as for life on Earth we have found that GRBs and in particular LGRBs are life threatening in a large part of the Milky Way as well as in many other locations in the Universe. The safest environments to preserve life are the outskirts of large galaxies in low density regions (so that these galaxies don’t have “dangerous” low metallicity dwarf satellites). It is curious to point out that a cosmological constant of about the same order of magnitude as the present value is essential for the Universe to grow large galaxies and also preserve low density regions at late times $z < 0.5$; the expansion history of a LCDM universe is modified in such a way that it provides enough time at high-$z$ for large under densities and galaxies to grow large. It is also worth mentioning that the damaging nature of GRBs could help explain Fermi’s paradox. We will investigate both of these question in detail in a forthcoming publication.

TP thanks the Institut Lagrange de Paris for hospitality while this work was being completed. This research was supported by the ERC grant GRBs, by the ISF I-CORE center of excellence and by an Israel-China grant. RJ thanks the Royal Society and the ICIC at Imperial College for financial support and hospitality while this work was being completed. We thank Chris Flynn and Luca Casagranda for discussions on the age-metallicity relation of stars in the Milky Way and the anonymous referees for their constructive and useful comments.

*tsvi.piran@huji.ac.il†raul.jimenez@icc.ub.edu

[1] Ruderman M. A., 1974, Sci, 184, 1079
[2] Thorsett S. E., 1995, ApJ, 444, L53
[3] Dar, A., Laor, A., & Shaviv, N. J. 1998, Physical Review Letters, 80, 5813
[4] Dar A., De Rujula A., 2001, astro, arXiv:astro-ph/0110162
[5] Scalo, J., & Wheeler, J. C. 2002, Astrophys. J., 566, 723
[6] Melott, A. L., Lieberman, B. S., Laird, C. M., et al. 2004, International Journal of Astrobiology, 3, 55
[7] Thomas, B. C., Jackman, C. H., Melott, A. L., et al. 2005, The Astrophysical Journal Letters, 622, L153
[8] Thomas B. C., et al., 2005, ApJ, 634, 509
[9] Melott A. L., Thomas B. C., 2009, Paleobiology, 35, 311
[10] Karam, P. A. 2002, Health Physics, 82, 491
[11] Stanek K. Z., et al., 2006, AcA, 56, 333
[12] Melott A. L., 2006, astro, arXiv:astro-ph/0604440
[13] Bromberg O., Nakar E., Piran T., Sari R., 2013, ApJ, 764, 179
[14] Woosley S. E., Bloom J. S., 2006, ARA&A, 44, 507
[15] Eichler D., Livio M., Piran T., Schramm D. N., 1989, Nature (London), 340,126
[16] Bromberg, O., Nakar, E., & Piran, T. 2011, The Astrophysical Journal Letters, 739, L55
[17] Palmer, D. M., Barthelmy, S., Gehrels, N., et al. 2005, Nature (London), 434, 1107
[18] Fishman G. J., Inan U. S., 1988, Natur, 331, 418
[19] Melott A. L., Thomas B. C., 2011, AsBio, 11, 343
[20] Melott A. L., Thomas B. C., 2012, Natur, 491, 1
[21] Usoskin I. G., Kromer B., Ludlow F., Beer J., Friedrich M., Kovaltsov G. A., Solanki S. K., Wacker L., 2013, A&A, 552, LL3
[22] Wanderman D., Piran T., 2010, MNRAS, 406, 1944
[23] Jimenez R., Piran T., 2013, ApJ, 773, 126
[24] Natarajan, P., Bloom, J. S., Sigurdsson, S., et al. 1997, New Astronomy, 2, 471
[25] Fynbo, J. P. U., Jakobsson, P., Möller, P., et al. 2003, Astronomy & Astrophysics, 406, L63
[26] Savaglio, S. 2013, EAS Publications Series, 61, 381
[27] Levesque, E. M. 2014, PASP, 126, 1
[28] Cucchiara, A., Fumagalli, M., Rafelski, M., et al. 2014, arXiv:1408.3578
[29] Fruchter A. S., et al., 2006, Natur, 441, 463
[30] Svensson K. M., Levan A. J., Tanvir N. R., Fruchter A. S., Strolger L.-G., 2010, MNRAS, 405, 57
[31] Nakar E., 2007, PhR, 442, 166
[32] Berger E., 2013, arXiv, arXiv:1311.2603
[33] Wanderman D., Piran T., 2014, arXiv, arXiv:1405.5878
[34] Soderberg, A. M., Kulkarni, S. R., Nakar, E., et al. 2006, Nature (London), 442, 1014
[35] Casagrande L., Schönrich R., Asplund M., Cassisi S., Ramírez I., Meléndez J., Bensby T., Feltzing S., 2011, A&A, 530, A138
[36] Panter B., Jimenez R., Heavens A. F., Charlot S., 2008, MNRAS, 391, 1117
[37] Ejzak L. M., Melott A. L., Medvedev M. V., Thomas B. C., 2007, ApJ, 654, 373
[38] Panter, B., Jimenez, R., Heavens, A. F., & Charlot, S. 2007, MNRAS, 378, 1550
[39] McMillan, P. J. 2011, MNRAS, 414, 2446
[40] Bovy, J., & Rix, H.-W. 2013, Astrophys. J., 779, 115