Mem. S.A.It. Vol. 81, 460

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Can gamma ray bursts be used as effective tracers of star formation to high Z?

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Abstract. Long duration gamma ray bursts (GRB's) have been identified as originating in type II SNa explosions, produced during the late stage evolution of massive stars. As the lifetimes of their progenitors are so short the GRB rate per unit (comoving) volume of space, on scales which include significant numbers of galaxies, could be proportional to the star formation rate (SFR), at least to the formation rate of massive stars. Unfortunately both theory and observation imply that those SNe which give rise to gamma ray bursts occur in stars of low metallicity, less than half an order of magnitude lower than solar. Here we examine the evidence and show that although some workers believe that it is possible to use local galaxies with GRB's to calibrate the SFR in more distant galaxies others claim that this may be possible given independent ways of determining the metallicities of the distant galaxies, while others suggest that it is too difficult, at least with present measurements, to use GRB's to determine the SFR at values of redshift higher than 5. We conclude that although their intrinsic power gives GRB's the facility to guide observers towards star forming galaxies, only by also using complementary indicators will we be able to make plausible determinations of the SFR as a function of epoch beyond z = 5, i.e. during the first 2 Gyr after the Big Bang.

Key words. Gamma-rays:– Bursts –Stars: –Star formation rate – Cosmology:– Cosmic timescale

1. Introduction

Gamma ray bursts, and in particular long duration gamma ray bursts, are known to be produced as the dying outbursts of massive star. Measure in units of the mean stellar lifetime these massive stars have lifetimes so that their death rates are essentially equal to their birth rates. The number of long duration gamma ray bursts may therefore be proportional to the star formation rate (SFR). At the present time gamma ray bursts can be detected more easily and reliably out to high redshift, z, than their underlying galaxy populations. So by measuring the redshifts of a sample population of GRB host galaxies it should be possible to derive, with useful statistical accuracy, the star formation rate per unit commoving volume over a large fraction of cosmological time. Apart from the basic importance of this information in deriving an updated and more rep-

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resentative version of the original Madau plot of the SFR density per unit commoving volume as a function of redshift (Madau, Pozzetti, & Dickinson, 1998), it would help to throw light on a number of related problems, notably whether the reionization of the universe, known to have occurred between z = 20 and z = 6, was caused by AGN's or by stars.

2. The objections and counter objections

The key objection is that models of gamma ray bursts show that these are favoured by a low metallicity in the star undergoing the supernova, o final cataclysm. Indeed the majority of theorists working on this problem would say that for a metallicity greater than 0.3solar a stellar explosion will not yield a gamma ray burst (see the review by Woosley and Bloom, 2006). The physical reason for this is that high metallicities give rise to high mass loss rates from the star before they explode, which leave insufficient mass and kinetic energy in the outburst to produce a GRB jet. This condition leads to several possible reasons why the rate of long duration GRB's may not be proportional to the SFR, and indeed, extrapolating to the range in z where the only available parameter is the GRB rate this could be a very misleading indicator for the SFR.

The first argument is that as the metallicity in the universe as a whole was lower at higher z, a calibration based on the number of GRB's per unit volume for a more local sample,(say for z < 4), where a number of alternative SFR indicators are available, will give a conversion factor for the ratio SFR:GRB which is too high to be used correctly at high z. This excess has been estimated as being as high as 4 between the range close to z = 4, and the range 6 < z < 10. Further details of this will be given below. A Madau plot based on the GRB rate in the latter range will show a false excess of SFR at epochs earlier than z = 6, if this argument is valid.

There is, however, an argument which works in just the opposite direction. As the metallicity of a galaxy varies positively with its mass, low mass galaxies are less metallic so the final explosions of massive stars in low mass galaxies will yield a higher fraction of GRB's. We can detect GRB's to higher redshifts than we can detect the low mass end of the galaxy mass function, and low mass galaxies at high z may well be contributing the major fraction of the SFR in the universe. So the GRB's may be able to provide us with a much better value for the SFR than any other method presently available. Factors of at least 4 favourable to the GRB method at z > 6 have been proposed.

3. Some relevant observational evidence.

3.1. SWIFT observations.

The SWIFT satellite gave the opportunity not only to detect many GRB's but to locate them via their X-ray emission, and hence to make a number of different types of observations of their host galaxies, notably their redshifts, but also their basic physical parameters: mass, metallicity, and in some cases the SFR could be measured by alternative methods. This enabled Yüksel et al. (2008) to estimate the relative SFRs from measurements on 63 GRB's, in three redshift ranges: 1 > z < 4, 4 < z < 5, and 5 < z < 7. Although the numbers in the two ranges at higher redshift were small it was possible to attempt a useful version of the Madau plot at redshifts beyond z = 5. They did so based on comparisons between the GRB's, Lyman break galaxies and Lyman emitters, to make an estimate of how the ratio GRB rate/ SFR increases to higher z, and hence to procure a "model independent" estimate of the star formation history at z > 4. Their Madau plot" is shown in Fig. 1, (which is Fig. 1 of Yüksel et al, 2008). This is a reasonable way to proceed, but the possibility of systematic error in the results beyond z = 5 is still high.

3.2. GRB's are favoured by low metallicity environments

The relation between the presence of a GRB and the metallicity of the galaxy has itself been well established observationally. An example

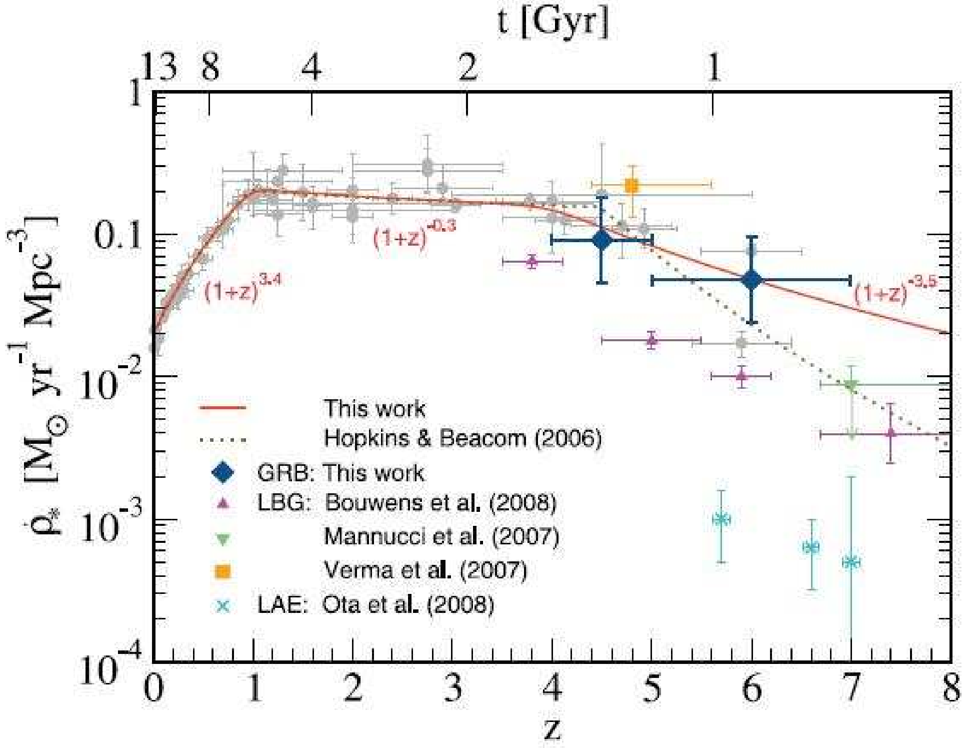

Fig. 1. Cosmic star formation history, the "Madau Plot" from Yüksel et al. (2008). Most of the data are from classical UV measurements. They are the fainter points, summarized in the dotted curve of Hopkins and Beacom (2006). The GRB contributions are the two dark points at z = 4 and z = 6, and the revised SFR is plotted as the darker continuous line. The GRB data have raised the SFR at higher z, but note that only two independent data points have been created from the Swift data, and that metallicity considerations are not fully dealt with (see text).

of this can be found in Modjaz et al. (2008) who used the oxygen abundance as a metallicity index in a set of local galaxies where GRB's had been observed and in a control sample with no GRB's. Fig. 2, (which is Figure 5 in Modjaz et al.) shows the dichotomy very clearly. The GRB's all occurred in galaxies with low metallicity, while in galaxies with higher metallicity they were not found. Their result was robust whichever of the various different methods for determining the oxygen abundance was employed. Kocevski et al. (2009) looked at this problem in quite a comprehensive way. They plotted the mass-metallicity relationship of galaxies in distinct redshift ranges from 1 to 5, the SFR against galaxy mass in the same range bins, the galaxy mass functions in each range, and the SFR against galaxy mass in each range. Using metallicity data from Savaglio, Glazebrook and LeBorgne. (2009) and from Castro-Ceron et al. (2008) they went on to show, taking into account the locally measured upper limit on the metallicity of galaxies which host GRB's, that beyond z= 4 the combination of the larger fraction of low mass galaxies with the lower overall metallicity should ensure that the GRB rate is indeed proportional to the SFR. This result is certainly plausible, but it does not resolve the problem by itself, as it does not allow us to calibrate this relationship us-

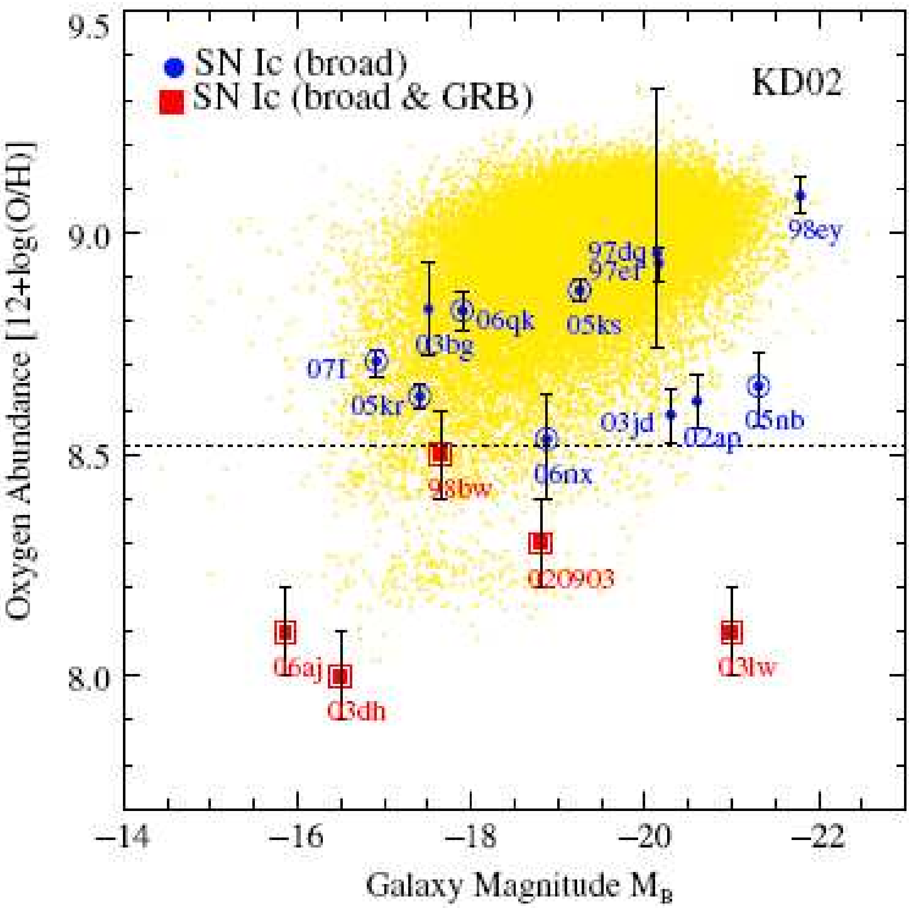

Fig. 2. Host galaxy luminosity (M_B), and metallicity measured via the Oxygen abundance, at the sites of nearby broad-lined SN Ic (SN Ic "broad") (circles) not connected with long duration GRB's, and SN Ic with broad lines connected with GRB's (broad+GRB) (squares) from Modjaz et al. (2008). This shows very clearly that those SNe Ic which yield GRB's are found in the low metallicity galaxies. The range of local star forming galaxies from the SDSS is the shaded patch of dots, showing that the GRB hosts are not typical of local galaxies (but may be more typical of high-z galaxies which tend to have lower metallicities).

ing nearby galaxies, where these conditions do not hold.

3.3. Using the GRB rate to probe the metallicity evolution at high z

Li (2008) had the neat idea of using the GRB rate to sample the metallicity evolution to high z. To do this he had to assume that the SFR can be measured independently. To this end he estimated the dust extinction in the rest-frame UV (a band usually used to try to determine the SFR), which he admitted is an increasingly sketchy and unreliable measurement beyond z = 4, and is in any case some function of the SFR itself. On the basis of the UV measurements of Hopkins and Beacom (2006) and of Bouwens et al. (2008), and other authors, and using his dust extinction correction he then produced a version of the Madau plot out to z = 7.4, as shown in Fig. 3. We should note how different this is from the version of Yüksel

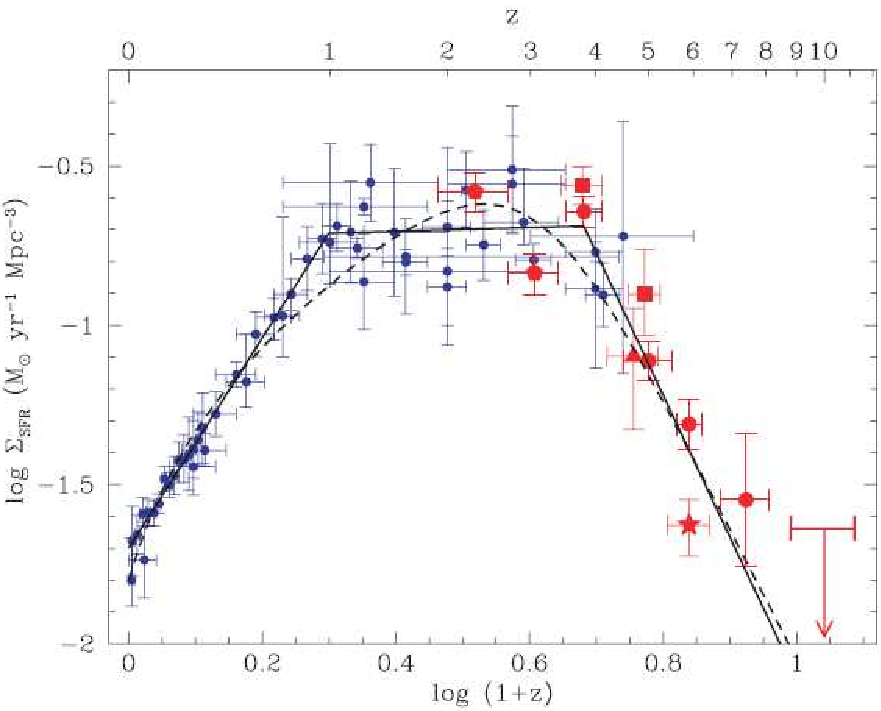

Fig. 3. History of star formation density in the universe (Madau plot) compiled by Li(2008) from standard UV and IR data. The curve for $z > 4$ is defined mainly by UV data from Bouwens et al. (2008) (larger filled circles). Li used this compilation in order to make a calibration of the effects of metallicity on the observed relationship between the GRB density and the SFR density as a function of z, assuming that this plot is itself valid. Without questioning its intrinsic validity, we note the striking difference from the Madau plot in Yüksel et al. (2008) which shows the difficulty of taking the metallicity effect quantitatively into account.

et al. (2008)! He then went on to plot the observed set of GRB's with measured redshift as a histogram, and compared this with the result of a simple model in which the "observed" SFR in Fig.3 is folded with an observational z-dependence of metallicity. He claimed that the good agreement shows that his estimate of this z-dependence is essentially correct. However the major discrepancy between his Madau plot and the carefully derived plot of Yüksel et al. (2008) should cause us to take this result as interesting conceptually, but not necessarily reliable quantitatively.

3.4. An initial use of Spitzer data.

Chary et al. (2007) used Spitzer to look for three GRB host galaxies at redshifts close to 5, of which they detected only one, GRB 0605108 at $z = 4.942$. They then plotted their detection and two non-detections on a histogram of the 3.6 m magnitudes of galaxies in the GOODS field, in the range $4.5 < z < 5.5$, showing that the GRB hosts are to the faint end of the distribution. They also confirmed that these luminosities are 2 to 3 times fainter than field galaxies at similar redshifts, but that these galaxies fall well within the distribution of GRB galaxies at much lower redshift ($z = 1$). They claim to have shown from this that the GRB hosts are a constant fractional representative of the total star forming galaxy population, and that that they can therefore be used directly to explore the SFR density to high z. This sweeping deduction is based on 1 detection and 2 non-detections, and in any case shows serious discrepancy from the suse-

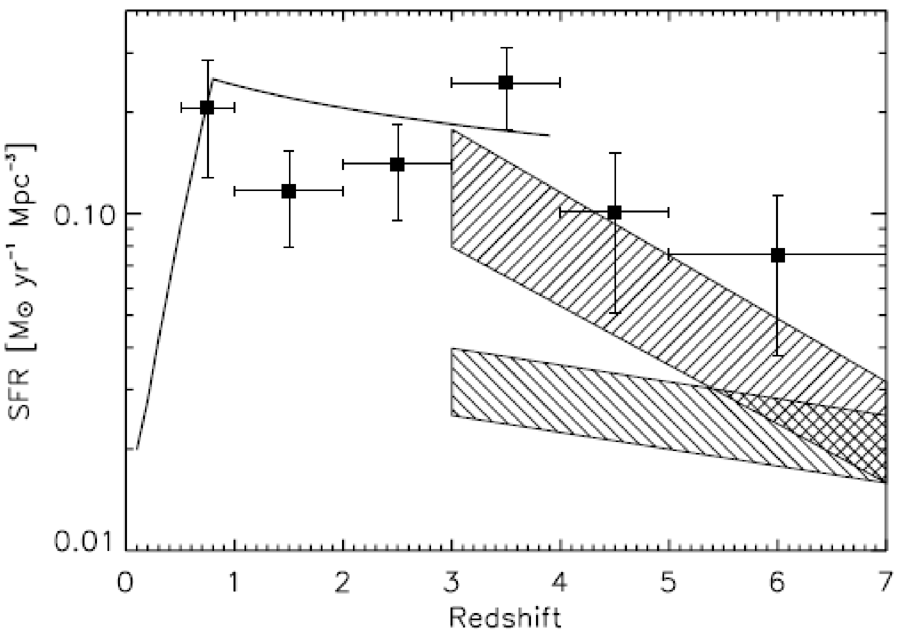

Fig. 4. Star formation rate density as a function of redshift for z > 4 inferred by Chary et al. (2007), from Swift long duration GRB's (squares). The solid black line is the extinction corrected SFRD at z < 4 from multiwavelength surveys in the IR and submm. These are used to calibrate the relationship between GRB density and SFR density. Lower hatched region is extinction uncorrected SFRD from rest-frame UV surveys, while upper hatched region contains the same data but corrected for reddening. Chary et al. claim that this SFRD is consistent with that from the GRB's, for z > 4, but of course state that more GRB's at high redshift would be needed to see whether the trend to a higher SFRD at z > 5 from the GRB's is realistic. This result is characteristic of the difficulties of using GRB's directly to measure the SFRD at high z.

quent work of Yüksel et al. (2008). However as well as their Spitzer measurements they used absorption spectroscopy to estimate the HI column densities for their three host galaxies, finding values of log Ne (column density) of between 21 and 21.6 (in logarithmic units of cm^{-2}), which makes them damped Ly-α systems, and with metallicities below 0.15 solar, and plotted the IR magnitudes or upper limits on a diagram of magnitude v. metallicity containing data from a large number of local galaxies from the Sloan Survey. They generalized to reach the conclusion that the metallicity of galaxies has increased with time more slowly than their stellar mass, probably because of the expulsion of metals from low mass galaxies. Finally they produced the obligatory Madau plot of SFR density v. redshift, shown here in Fig. 4. The solid black line is the SFRD for z < 4, from extinction corrected mid-IR and submm surveys, used to calibrate the GRB hosts. The lower hatched zone is the uncorrected SFRD from rest-frame UV surveys, and the upper hatched zone is this SFRD corrected for extinction. The points represent values of the SFRD obtained by extrapolation from the GRB hosts. According to Chary et al. (2007), the points at z > 4 are consistent with the extinction corrected UV plot, but we must note that the numbers of GRB's with values of z > 5 was still tiny, and the complex issues of dependence on size and metallicity of the galaxies concerned have not yet been resolved in this work. Work is, of course proceeding in this area, and we note here the use by Calura et al. (2009) of spectroscopic observations of the host galaxies of 4 long duration GRB's by Prochaska et al. (2007) to test models of chemical evolution applied to these objects. Among their conclusions they confirmed that GRB's do occur in low metallicity galaxies with low star formation efficiency.

4. Conclusions

From the outline of recent work attempting to quantify the relation between star formation rate density and GRB density as a function of redshift we can set out some interim conclusions. Long duration GRB's are found preferentially in low metallicity star forming galaxies, and there is no doubt that they are indeed tracers of star formation. However their metallicity dependence, which is useful as a diagnostic for their production mechanism, presents a dilemma in their use as an SFR density tracer at high z. Low metallicity is typical of low mass galaxies, at least in part because they lose metals to the IGM more easily via their galactic winds. But low metallicity is in any case a property of the earlier universe at z >(say) 5. So to disentangle the two effects we must have an adequate calibration plan, which requires measuring SFR's, metallicities and luminosites of many GRB hosts from (say) z = 2 to z as high as we can. The situation is further complicated by the fact that the luminosity function of the star forming galaxies changes with z, in the direction of a higher proportion of dwarf galaxies at higher z. This may eventually work in our favour, as the GRB hosts might be virtually all the star forming galaxies at high z, i.e. essentially all galaxies which form stars at high z may be low metallicity dwarfs. But to show this we will almost certainly have derived the Madau plot using other types of observations anyway! Nevertheless the GRB's may well guide us towards the star forming galaxies and can be a useful aid in strengthening our quantification of the plot to high z.

Acknowledgements. The work for this article was supported by proyects 310368 of the Instititutto de Astrofsica de Canarias, and AYA207-67625-CO2-01 of the Spanish Ministry of Science and Innovation.

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