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Massive star-formation rates of γ-ray burst host galaxies: An unobscured view in X-rays

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Abstract. The hard X-ray (2–10 keV) luminosity of a star-forming galaxy tracks its population of high mass X-ray binaries and is essentially unobscured. It is therefore a practically unbiased measure of star-formation in the host galaxies of γ-ray bursts (GRBs). Using recent and archival observations of GRBs with the *XMM-Newton* and *Chandra* X-ray observatories, limits are placed on the underlying X-ray emission from GRB hosts. Useful limits on the current massive star-formation rates (SFRs), unaffected by obscuration, are obtained for the hosts of three low redshift GRBs: GRB 980425, GRB 030329 and GRB 031203. These limits show that though the specific SFRs may be high (as in dwarf starburst galaxies), none have massive obscured star-formation at the levels implied by the sub-mm detection of some GRB hosts. It is also shown that in cases where the faint luminosities of the late time afterglow or supernova emission are of interest, the contribution of the host galaxy to the X-ray flux may be significant.

Key words. gamma rays: bursts – X-rays: galaxies – X-rays: binaries – galaxies: starburst

1. Introduction

Long-duration γ-ray bursts (GRBs) coincide with the demise of certain massive stars (e.g. Hjorth et al. 2003; Stanek et al. 2003). Because their detection in γ-rays is unaffected by intervening gas and dust, they provide a powerful, unbiased tracer of the location of high-redshift star-formation and thus allow a new means of identifying and studying distant star-forming galaxies. However, the majority of GRB host galaxies appear to be sub-luminous ($\langle R \rangle \sim 25$) and blue (Fruchter et al. 1999; Le Floc'h et al. 2003). Furthermore none are Extremely Red Objects (though Levan et al. 2004, show that the host galaxy of GRB 030115 is very red) and few have detectable sub-mm (Smith et al. 1999, 2001; Barnard et al. 2003; Berger et al. 2003) or FIR fluxes (Hanlon et al. 1999, 2000). GRBs also generally occur within UV-bright parts of their hosts (Bloom et al. 2002), which is surprising if star-formation is generally obscured (Elbaz et al. 2002; Goldader et al. 2002; Metcalfe et al. 2003; Sato et al. 2004). Le Floc'h et al. (2003) have asked "Are the hosts of gamma-ray bursts sub-luminous and blue galaxies?" This raises the further question of whether a sizable proportion of global star-formation actually occurs in small and relatively unobscured, modestly star-forming galaxies that are too faint to appear in other surveys of star-formation activity, or whether GRBs trace only a fraction of the star-forming population, for example due to metallicity effects (MacFadyen & Woosley 1999; Fynbo et al. 2003).

In this paper we examine the limits that can currently be placed on the star-formation rates (SFRs) of GRB host galaxies using an unobscured, and potentially unbiased tracer of star-formation: the high mass X-ray binary (HMXB) population, via their aggregate hard X-ray (2–10 keV) luminosity (see Grimm et al. 2003; Ranalli et al. 2003; Gilfanov et al. 2004a; Persic et al. 2004). This measure has been shown to be linearly related to the current massive SFR at redshifts up to $\sim$1. The following relations are given by Grimm et al. (2003) and Persic et al. (2004) respectively for the massive and the total SFRs: $SFR(\geq 5\,M_{\odot}) = 1.5 \times 10^{-40} \times L_{2-10}\ \ M_{\odot}\,\mathrm{yr}^{-1}$, and $SFR(\geq 0.1\,M_{\odot}) = 10^{-39} \times L_{2-10}^{\mathrm{HMXB}}\ \ M_{\odot}\,\mathrm{yr}^{-1}$, with luminosities in $\mathrm{erg\,s^{-1}}$. As long as the massive SFR is relatively high ($\gtrsim 4.5\,M_{\odot}\,\mathrm{yr}^{-1}$; Gilfanov et al. 2004a), the linear relation holds. Where the SFR is lower than this, the relation becomes non-linear due to the statistical properties of the combined emission of a small number of discrete sources (Gilfanov et al. 2004b); $SFR(\geq 5\,M_{\odot}) = (3.8 \times 10^{-40} \times L_{2-10})^{0.6}\ \ M_{\odot}\,\mathrm{yr}^{-1}$ (Grimm et al. 2003). In this paper, we derive upper limits to the SFR in GRB host galaxies by assuming the 2–10 keV luminosity is due exclusively to HMXBs (taking into account the 20% scatter in the above relation; Persic et al. 2004).

In Sect. 2 selection criteria, details of the observations, and our X-ray data reduction are described. The resulting detections and limits are outlined in Sect. 3. The potential and limitations of the technique are described in Sect. 4 and the implications of our results are discussed in Sect. 5. A cosmology where $H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\Lambda = 0.7$ and $\Omega_\mathrm{m} = 0.3$ is assumed throughout.

2. Sample, observations, and data reduction

All available follow-up observations of GRBs or X-ray Flashes with *Chandra* and *XMM-Newton* performed before May 2004 were used in the analysis. Where redshifts for the burst or its host galaxy were available in the literature, these values were used (see Table 1). Data from earlier X-ray missions were not included.

As an initial selection mechanism, results previously published or made available in preliminary form (generally via GRB Coordinates Network circulars), were examined in order to find datasets that might provide strong constraints on the massive SFRs in GRB host galaxies. Details of all GRB localisations observed with *Chandra* and *XMM-Newton* are provided in Table 1. From these data it was immediately apparent that only a small number provided potentially strong constraints: GRBs 980425, 030329 and 031203, all of which are associated with spectroscopically confirmed SNe. The results for these hosts are produced separately in Table 2.

It is not possible to disentangle the emission contributed by the late GRB afterglow, the GRB (or supernova [SN]), or the HMXB and low mass X-ray binary populations (or indeed a low-luminosity AGN) in any of these cases except GRB 980425. However, we can at least derive useful upper limits on the HMXB flux and therefore on the SFR in the host galaxy by considering the aggregate flux from all of these components in a given galaxy. Therefore it is the total flux measurement that is considered below apart from the host galaxy of GRB 980425 (see Sect. 3).

The *Chandra* datasets for GRB 980425 and GRB 031203 were reduced and analysed using CIAO version 3.0.3 with the CALDB 2.26 version of the calibration archive, and it is this analysis that is used in the paper. To calibrate the count-rate to flux conversion, the count-rate was used as the normalisation for an absorbed power-law model, with absorption set at the Galactic value and the best-fit power-law photon index; where there was insufficient data to determine the power-law index, $\Gamma = 1.2$ was assumed (the emission in these star-forming galaxies is expected to be dominated by the HMXB emission where the mean Γ is ~1.2; Persic et al. 2004). For each burst the deepest limit is quoted.

Table 1. Data from the observations of all long-duration GRBs observed with *Chandra* or *XMM-Newton* that place the lowest limit available on the flux.

GRB	Observatory	t_burst (days)	Range (keV)	Flux (10^{-15} erg cm^{-2} s^{-1})	z	Luminosity[1] (10^{44} erg s^{-1})
040223	N	0.75	2–10	170[2]	–	–
040106	N	0.72	2–10	400[3]	–	–
031220	C	19	2–10	<3[4]	–	–
031203	C	50	2–10	4[5]	0.1055[6]	0.099
030723	C	14	0.5–8	<0.5[7]	–	–
030528	C	12	2–10	4.9[8]	–	–
030329	N	258	0.5–2	0.6[9]	0.1685[10]	0.041
030328	C	0.64	0.5–3	190[11]	1.52[12]	2434
030227	N	0.81	0.2–10	400[13]	1.6[13]	5818
030226	C	1.5	2–10	32[14]	1.986[15]	791
021004	C	52	2–10	0.7[16]	2.33[17]	25.6
020813	C	43	0.6–6	1450[18]	1.255[19]	11571
020427	C	17	2–10	19[20]	–	–
020405	C	1.7	0.2–10	1360[21]	0.691[22]	2490
020322	N	0.86	0.2–10	320[23]	–	–
020321	C	9.9	2–10	<4[24]	–	–
020127	C	14.3	2–10	26[25]	–	–
011211	N	0.81	0.2–10	80[26]	2.140[27]	2375
011130	C	82	2–10	<21[28]	–	–
011030	C	30	2–10	7	–	–
010222	C	8.7	2–10	72[29]	1.477[30]	859
010220	N	0.87	0.2–10	33[31]	–	–
001025A	N	910	0.3–12	<4[32]	–	–
000926	C	13	1.5–8	3.6[33]	2.0379[34]	94.9
000210	C	0.93	2–10	180[35]	0.846[35]	542
991216	C	1.6	2–10	2300[36]	1.02[37]	10990
980425	C	1281	2–10	13[38]	0.0085[39]	0.0018

[1] No bandpass or k-corrections applied; [2] Tiengo et al. (2004a); [3] Reeves & Watson (2004); [4] assuming source #1 (Gendre et al. 2004); [5] this paper ($\Gamma = 1.7$); [6] Prochaska et al. (2004); [7] Butler et al. (2003b); [8] Butler et al. (2003a); [9] Tiengo et al. (2004b); [10] Hjorth et al. (2003); [11] Butler et al. (2003c); [12] Martini et al. (2003); Rol et al. (2003); [13] Watson et al. (2003); [14] Pedersen et al. (2003); [15] Greiner et al. (2003); [16] Sako & Harrison (2002); [17] Møller et al. (2002); Matheson et al. (2003a); Schaefer et al. (2003); [18] Vanderspek et al. (2002); [19] Barth et al. (2003); [20] Fox (2002b); [21] Mirabal et al. (2003); [22] Masetti et al. (2003); Price et al. (2003); [23] Watson et al. (2002b); [24] see In't Zand et al. (2002); [25] Fox (2002a); [26] Reeves et al. (2002); [27] Holland et al. (2002); [28] no single source found (Butler et al. 2002); [29] Harrison et al. (2001a); [30] Jha et al. (2001); Masetti et al. (2001); Galama et al. (2003); [31] Watson et al. (2002a); [32] Pedersen et al. (2004); [33] Harrison et al. (2001b); [34] Castro et al. (2003); [35] Piro et al. (2002); [36] Piro et al. (2000); [37] Vreeswijk et al. (1999); Piro et al. (2000); [38] Kouveliotou et al. (2004); [39] Galama et al. (1998).

3. Results

ESO 184-G82, the host galaxy of GRB 980425, is the closest known GRB host and is the only one that is substantially spatially resolved with X-ray instruments. The spiral optical morphology appears to exclude a galaxy significantly larger than is seen in visible light. The X-ray flux within the optical extent of the galaxy is entirely dominated by two point sources ~1.5″ apart, one of which is coincident with the radio position of SN1998bw and is almost certainly associated with it (Kouveliotou et al. 2004). Removing this source's contribution yields a total 2–10 keV flux for the galaxy of $7 \pm 3 \times 10^{-15}$ corresponding to a luminosity of $1 \pm 0.4 \times 10^{39}$ erg s^{-1}, a massive *SFR* of $0.5 \pm 0.3\ M_\odot\,\mathrm{yr}^{-1}$ (using the non-linear relation for low-luminosity galaxies found by Grimm et al. 2003) and a total *SFR* of $2.8 \pm 1.9\ M_\odot\,\mathrm{yr}^{-1}$ using the (Salpeter) IMF adopted by Persic et al. (2004) with the massive SFR derived immediately above. While it is noted that the galaxy appears to be actively star-forming (Fynbo et al. 2000), this is the first measure of its global SFR to our knowledge.

Table 2. X-ray observations of GRB positions with total *SFR* limits <1000 $M_\odot$/yr.

GRB	Flux (10^{-15} erg cm^{-2} s^{-1})	z	Luminosity[a] (10^{41} erg s^{-1})	Equivalent massive *SFR* ($M_\odot$/yr)
031203	6[b]	0.1055[c]	1.6	24
030329	3[d]	0.1685[e]	2.1	32
980425	7[f]	0.0085[g]	0.01	0.5

[a] Rest frame, 2–10 keV; [b] assuming $\Gamma = 1.2$; [c] Prochaska et al. (2004); [d] Tiengo et al. (2004b); [e] Hjorth et al. (2003); [f] afterglow contribution removed; [g] Galama et al. (1998).

GRB 030329 was monitored over 258 days with *XMM-Newton* and in the final observation, the afterglow was barely detected, with a 0.5–2.0 keV flux of 6.2×10^{-16} erg cm^{-2} s^{-1} (Tiengo et al. 2004b). The rest-frame 2–10 keV luminosity was $\sim 2 \times 10^{41}$ erg s^{-1}, implying a massive *SFR* of at most $31 \pm 13\ M_\odot$ yr^{-1} corresponding to a total *SFR* of $\lesssim 200 \pm 80\ M_\odot$ yr^{-1}. Though the host is very faint, estimates from optical observations (Hα and [O II] measures) suggest a total *SFR* of $\sim 0.2\ M_\odot$ yr^{-1} (Hjorth et al. 2003) or $\sim 0.5\ M_\odot$ yr^{-1} (Matheson et al. 2003b), consistent with the X-ray upper limit. Hjorth et al. (2003) suggest the host must be a dwarf starburst galaxy, a finding confirmed by Matheson et al. (2003b).

The host galaxy of GRB 031203 (HG 031203) was detected in the near-infrared, however no optical/NIR GRB afterglow was discovered initially (though see Malesani et al. 2004, who subtracted the host galaxy light from early data). We recently obtained ~30 ks of Director's Discretionary Time to observe the HG 031203 with *Chandra* (Ramirez-Ruiz et al. in preparation). We found a faint X-ray point source with a flux of $4 \pm 3 \times 10^{-15}$ erg cm^{-2} s^{-1} (2–10 keV), assuming a power-law photon index of 1.7, consistent with the extrapolation of the afterglow decay rate observed in the previous two observations. If we instead assume a typically hard HMXB spectrum ($\Gamma = 1.2$), this corresponds to a luminosity of 1.5×10^{41} erg s^{-1} implying a massive *SFR* of at most $24 \pm 17\ M_\odot$ yr^{-1}, corresponding to a total *SFR* of $\lesssim 150 \pm 110\ M_\odot$ yr^{-1}. X-ray emission from the region surrounding the galaxy out to 8″ radius is consistent with the background level. HG 031203 is quite bright ($I \sim 19.3$ mag), though very nearby ($z = 0.1055$) for a GRB host galaxy, and is blue with low metallicity and little internal extinction (Prochaska et al. 2004). The total *SFR* is $>11\ M_\odot$ yr^{-1} based on the Hα luminosity (Prochaska et al. 2004), consistent with the X-ray upper limit above. Interestingly, this SFR implies a radio flux of ~0.3 mJy (using the assumptions and Eq. (1) of Berger et al. 2003), somewhat above an upper limit published recently (Soderberg et al. 2004). We infer therefore, that a significant fraction of the flux detected during the second observation derives from the host galaxy. The fact that a host galaxy brighter than ~0.3 mJy is not observed, confirms the suggestion that there is not a large obscured star-formation fraction in this galaxy.

It follows from the above analysis that a fraction of the X-ray flux detected in observations of GRB afterglows comes from the HMXB population of the host galaxy. In the case of HG 031203, based on the *SFR* of $>11\ M_\odot$ yr^{-1}, we expect at least one count in a 30 ks *Chandra* ACIS-S observation to have its origin in the HMXBs of the host galaxy, rather than belonging to the GRB/SN. This is about 10% of the detected counts in the most recent observation.

4. X-ray luminosity as a SFR indicator

The hard X-ray (2–10 keV) SFR indicator is especially useful in cases of extreme obscuration as the X-rays are only seriously attenuated at low (<2 keV) energies, unless the absorbing column density is $\gtrsim 10^{23}$ cm^{-2}, corresponding to $A_V \gtrsim 100$ throughout most of the starburst (at the gas-to-dust ratios of the Galaxy). Another key advantage of the technique is the relatively high spatial resolution (~0.5″ with *Chandra*) and high localisation accuracy (typically ~0.3″ with *Chandra* and ~0.8″ with *XMM-Newton*) that means there is essentially no risk of misidentification of the source. In some cases there is the possibility of localising the dominant source of star-formation within a galaxy. This is in contrast to other observing bands that are unaffected by dust obscuration, the FIR, sub-mm and radio wavelengths, where the beam size is often $\gtrsim 10''$. The possibility of localising the sources of star-formation within a galaxy without having to worry about obscuration is especially interesting as GRBs generally occur within UV-bright parts of their hosts (Bloom et al. 2002). Finally, it is likely that the HMXB population traces the SFR in the same way as GRBs, since both are affected by many of the same effects (short-lived massive stars, possibly metallicity, binarity etc.).

The principle limitation of this estimate is the lack of sensitivity at high redshift, since even a moderately long (100 ks) *Chandra* exposure of a GRB host can only give a massive SFR limit of $\sim 500\ M_\odot$ yr^{-1} at redshifts $z \sim 1$. It should be mentioned however, that the linear relation between exposure time and limiting depth using *Chandra* is favourable to making very long observations of at least a few sources, in particular those at low redshift.

Even the small sample with useful constraints examined in this paper is likely to be biased to some extent. In the first case we obtain useful limits only at relatively low redshift, while it is apparent that the space density of ultraluminous infrared galaxies (ULIRGs) increases dramatically from low redshift to redshift ~1 (Elbaz et al. 2002). Second, it may be expected that fainter (and possibly X-ray rich) GRBs dominate the observed GRB rate at low z, a factor potentially related to many parameters (metallicity, orientation etc.). Otherwise, in terms of obscuration effects, this small sample should be unaffected.

5. SFRs of GRB host galaxies

A few GRB host galaxies have detectable FIR, sub-mm and/or radio detections, implying that they are ULIRGs: GRB 970508, GRB 000418, GRB 000210, GRB 980703 and GRB 010222 (Hanlon et al. 2000; Smith et al. 2001; Berger et al. 2003; Tanvir et al. 2004). It has been suggested that a considerable fraction of GRBs are hosted in ULIRGs (~20%, Berger et al. 2003). Though the large beam-size for the FIR, sub-mm and radio observations make an unambiguous association between the GRB and the ULIRG somewhat uncertain, the probability of a chance association is low. Curiously, these massive star-forming galaxies which should have fairly high internal extinctions exhibit blue colours and very low extinction in optical and NIR observations (Frail et al. 2002; Gorosabel et al. 2003a,b; Le Floc'h et al. 2003), making them appear at these wavelengths to be dust poor, star-forming dwarf galaxies. From the X-ray limits presented here however, it is apparent that the hosts of GRB 980425, GRB 030329, and GRB 031203 are unlike the host galaxies of the sub-mm–detected galaxies in spite of the similarities in their optical/NIR properties (blue colours, apparently moderate SFR).

Although a large, deep X-ray sample of GRB hosts would be very valuable, it would be expensive in terms of observing time. The association of ULIRGs as hosts of some GRBs can be tested directly however with only a few observations; long exposures with *Chandra* of the GRB ULIRG host galaxies, at least in the cases of the two strong claims for a ULIRG connection with lower redshifts, GRB 000210 and GRB 000418 would decide the issue. *Chandra* imaging in hard X-rays will allow an unambiguous association to be made and could confirm the sub-mm detection in an exposure time of ~250 ks.

Finally, it should be noted that in observations where the very faint fluxes associated with the late time afterglow or SN are of interest, the flux contribution from the host galaxy may be significant and should be accounted for.

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