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7 The morphology of GRB host galaxies

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Abstract. We study the morphology of a sample of gamma-ray burst host galaxies, in order to gain additional insight in the type of galaxy that gives rise to a gamma-ray burst, and in its star-formation nature. We use Hubble Space Telescope observations that were obtained after the afterglow has faded away. Fitting exponential disk (typical for spirals) and $R^{1/4}$ (typical for ellipticals) models to the surface brightness profiles of the 8 brightest host galaxies, we find that the disk model is slightly preferred, although two galaxies are fit best with an $R^{1/4}$ profile. We also measure the central concentration and asymmetry of 12 host galaxies, and compare these to the values of (1) galaxies in the Hubble Deep Field, and (2) all remaining galaxies that are present on the gamma-ray burst host images. Most host galaxies are situated in a region of the concentration-asymmetry diagram that is mainly occupied by Hubble Deep Field galaxies that are visually classified as spirals and peculiar/merging galaxies. Three hosts are situated in the region occupied by elliptical galaxies. These results show that GRB host galaxies do not fit into one clear single morphological class.

7.1 Introduction

There is mounting evidence that the progenitors of the class of long-duration gamma-ray bursts (GRBs) for which afterglows have been detected (for an overview, see Van Paradijs et al. 2000) are associated with regions of massive-star formation. Probably the best evidence is provided by the location of the afterglows with respect to their host galaxies (e.g. Bloom et al. 2001c; Fruchter et al. 2002). Fig. 7.1 shows a mosaic of 18 GRB host galaxies (from Fruchter et al. 2002), imaged with the Hubble Space Telescope
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(HST), for which an accurate projection of the position of the early afterglow is possible. This has resulted in an unambiguous identification of these host galaxies. The 1σ error in the afterglow projection is indicated by the circle in each image. Fruchter et al. (2002) show that the GRBs are more centrally concentrated on the peaks of the surface brightness than the light itself, suggesting a strong correlation between the locations of GRBs and bright regions of star-formation. Taking into account that GRB host galaxies tend to be bluer than field galaxies at similar redshifts (Fruchter et al. 1999b, 2002), and that they are actively star-forming galaxies (e.g. Kulkarni et al. 1998b; Djorgovski et al. 1998), this suggests that the progenitors of the long-duration class of GRBs are located in regions of massive-star formation. This is a strong argument in favour of the collapsar model, where the progenitor is a very massive star (Woosley 1993; MacFadyen & Woosley 1999).

Another line of evidence was initiated by the discovery of an unusual supernova of type Ic, SN 1998bw, in the error box of GRB980425 (Galama et al. 1998b). These authors calculated that the chance probability of the two phenomena to occur so close together on the sky and in time, is less than 10^{-4}. Since this discovery, several indications have been found for a supernova lightcurve component superimposed on the late-time powerlaw decay of the afterglow (Bloom et al. 1999a; Reichart 1999; Galama et al. 2000). The collapsar model predicts that every GRB produced by the collapse of a massive star, will be accompanied by a supernova of a type similar to SN 1998bw (MacFadyen & Woosley 1999), because the enormous energy release of the central black hole and surrounding torus not only induces the formation of jets along the rotational axis, but it also causes the envelope of the star to be blown away. Recently, an X-ray spectrum of the afterglow of GRB011211, observed with XMM-Newton, shows evidence for emission lines of Mg, Si, P, Ar, Ca, and possibly Ni that have an outflow velocity of 0.1c (Reeves et al. 2002). The authors argue that this is due to the relativistic fireball shock front running into an “envelope” that was ejected during a preceding supernova explosion.

If long-duration GRBs are associated with regions of massive-star formation, one can expect the host galaxies of GRBs to be very actively star-forming galaxies, possibly even starburst galaxies. These are galaxies which are converting most of their neutral gas content into stars in a very short period of time (∼ 10^8 yr). At least some GRB host galaxies are (very) gas-rich, which is demonstrated by the observation of (rest-frame) ultraviolet resonance lines (Lyα, Siiv, Civ, Mgii) in GRB afterglow spectra. A Lyα absorption line has been detected in 3-4 GRB host galaxies (Fynbo et al. 2002; Castro et al. 2001b; Jensen et al. 2001). If the proposed Lyα detection in the afterglow spectrum of GRB010222 is real, its strength indicates an HI column density of 5×10^{22} cm^{-2} (consistent with the value derived from X-ray afterglow observations; in’t Zand et al. 2001), making its host galaxy the strongest damped Lyα system known (Salamanca et al. 2002). From radio and sub-mm observations there are indications that at least some of the GRB hosts are starburst galaxies, with star-formation rates (SFRs) of several
Figure 7.1: HST images of 18 GRB host galaxies for which an accurate projection of the early afterglow position is possible. GRB970228 through GRB000418 were imaged with STIS (0''0254 drizzled pixels), and GRB000926 and GRB010222 with WFPC2 (0''05 drizzled pixels). The image are 2''5 on a side, except for GRB000926, which is 3''75×3''75. This mosaic shows that GRB host galaxies have a wide range in magnitude and in morphology.
hundred M\odot per year (Berger et al. 2001b; Frail et al. 2001a; Berger et al. 2001b). For
one case, however, an upper limit of 100 M\odot/year has been determined (Vreeswijk et al.
2001a), suggesting that GRB hosts cover a wide range in SFRs.

In this chapter we investigate the morphology of the GRB host galaxies, which provides
additional insight into the type of galaxy that gives rise to a GRB, its relation to other
galaxies at similar redshifts, and its star-formation nature. We use a sample of late-
time HST images of GRB hosts that were unambiguously identified through an accurate
projection of the early afterglow. This data set is described in § 7.2. Our study of
the morphology of these GRB hosts is divided into two main parts: in § 7.3 we fit exponential
and R\textsuperscript{1/4} surface brightness profiles to the hosts. This allows to make rough distinction
between early- and late-type galaxies. In § 7.4 we use the central concentration and
asymmetry indices in order to classify the galaxies as elliptical, spiral, or peculiar. We
discuss our results and present our conclusions in § 7.5.

7.2 The HST sample of GRB host galaxies

We make use of the observations of three programs that have imaged GRB host galaxies
over the past years. The principal investigators of these programs are: Fruchter (e.g.
Fruchter et al. 2000b), Kulkarni (e.g. Kulkarni et al. 1998b) and Holland (see Holland
et al. 2000). We have selected the host galaxies for which an accurate (\textquoteright\textquoteright.2) projection
of the early optical afterglow is possible, to avoid misidentification. Most galaxies were
imaged with STIS in the clear (50CCD) and longpass (LP) filters, except for the last two
hosts in our sample: GRB000926 and GRB010222, which were observed with WFPC2
in several filters. We use the 50CCD and F606 images. The images were bias-subtracted
and flat-field corrected by the HST pipeline, and then drizzled (Fruchter & Hook 2002)
to a resulting image with half the scale of the raw images, resulting in pixel size of
\textquoteright\textquoteright.0254 and \textquoteright\textquoteright.05 for the STIS and WFPC2 images, respectively. All images used were
taken sufficiently long after the burst, so the contamination from the early afterglow is
negligible. A mosaic of the selected 18 GRB host galaxies is shown in Fig. 7.1.

7.3 Exponential disk versus de Vaucouleurs profile

We fitted exponential and de Vaucouleurs models to the surface brightness profiles of the
8 brightest galaxies in the sample of GRB hosts. The noise in the images of the fainter
galaxies becomes too large for a meaningful comparison between the two models. Most
elliptical galaxies and bulges of spiral galaxies are well-fit with a de Vaucouleurs or R\textsuperscript{1/4}
profile: \( I(r) = I_e \exp \left(-7.669 \left(\frac{r}{R_e}\right)^{1/4}\right) \), where \( R_e \) is the effective radius corresponding
to the isophote which contains half of the galaxy light, and \( I_e \) is the surface brightness
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at \( R_e \). Disks of spiral galaxies, however, are best fit with an exponential profile: 
\[
I(r) = I_0 \exp\left(-\frac{r}{R_d}\right),
\]
where \( R_d \) is the disk scale length, and \( I_0 \) is the central surface brightness. Hence determining the best-fitting model may allow a distinction between these two classes of galaxies.

The fitting method is similar to the one used by Fruchter et al. (2000b), who fitted exponential and \( R^{1/4} \) profiles to the host of GRB 970508. For each image we first cut out a small area around the host galaxy, from which we build a Poisson error image. For each iteration in the fitting process, we create a 2-dimensional model image based on six parameters for both models. These parameters are: the central or effective surface brightness (\( I_0 \) or \( I_e \), respectively), the disk scale length or effective radius (\( R_d \) or \( R_e \), respectively), position angle (PA), axis ratio, and x and y pixel position. This model image is convolved with the point spread function (PSF) before fitting it to the observed object image. To create a PSF image that approximates the real PSF of the telescope and instrument as closely as possible, we drizzle several model PSFs (as many as there are dithered individual object images that were used to create the final object image). Such a “raw” model PSF can be produced with Tiny Tim software (Krist 1995). This subsampled PSF image is given a random offset in x- and y-position several times, just as the raw object images are offset with respect to each other, typically 10-20 pixels. These images are then rebinned to the original pixel size, convolved with the charge diffusion kernel and drizzled to the final PSF image using the same parameter values such as scale and rotation as in the drizzling run of the object image. As expected, the resulting PSF is similar to the PSF of stars in the STIS images. After convolution of the model image with this PSF, we use the AMOEBA fit routine in IDL to minimize \( \chi^2 = \frac{(\text{object-convolved}(\text{model,psf})}{\text{error}}^2 \). The errors for the fit parameters in Table 7.1 are estimated by increasing a particular parameter with a certain amount and holding it fixed at this value, while fitting for all the other parameters. The increase in the value for which the \( \chi^2 \) increases with unity is taken as the error in the parameter value.

We performed these fits for the 8 brightest host galaxies imaged with STIS. The results are shown in Table 7.1 and Fig. 7.2. The scale lengths and effective radii are converted to kpc, assuming the following cosmology: \( H_0 = 65 \text{ km/s/Mpc} \), \( \Omega_{\text{lambda}} = 0.7 \) and \( \Omega_{\text{matter}} = 0.3 \) (see Hogg 1999). The position angle is listed according to the usual convention, i.e. counterclockwise starting from 12 o’clock, or North. We note that the ellipticity (\( \epsilon \)) is related to the ratio of the minor axis and major axis length (\( b/a \)) in the following way: \( \epsilon = 1 - b/a \). We find that the exponential model clearly provides the best fit for the hosts of GRB 970508, GRB 980703 and GRB 990712. In the cases of GRB 991208 and GRB 000418, the data are best fit with a de Vaucouleurs profile, although for these galaxies the difference in \( \chi^2 \) between the two models is not very large. For the other galaxies, both models fit the data equally well.

\footnote{see www.stsci.edu/software/tinytim/}
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We overestimated the errors in position angle based on the almost circular shape of this galaxy: axis ratio = 0.96. The low values for the $x^2$ suggest that a normal distribution is assumed that $H_0 = 65$ km/s/Mpc. The central position is 0.7 and 0.3 for the host of GRB 991206 the error estimation for the angle is about 0.3, we used $x$ degrees from the calculation of the angular diameter distance (see Hoeg 1999). The position angle is listed in the usual STIS V-band zero point of 20.3 for a count source, and a difference of $R_{2031}$. We also used the table parameters for the conversion from intensity to surface brightness we used the

| $x$ | $y$ | $z$ | $w$ | $v$ | $u$ | $t$ | $s$ | $r$ | $q$ | $p$ | $o$ | $n$ | $m$ | $l$ | $k$ | $j$ | $i$ | $h$ | $g$ | $f$ | $e$ | $d$ | $c$ | $b$ | $a$ | $z$ | $y$ | $x$ |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1.8 | 1.3 | 1.8 | 1.2 | 1.7 | 1.1 | 1.4 | 0.9 | 1.0 | 0.7 | 0.5 | 0.3 | 0.2 | 0.1 | 0.0 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 | 0.0 | 0.8 | 0.7 | 0.6 | 0.5 |

Table 1: Exponential and $R_{1/4}$ profile fit parameters for the conversion from intensity to surface brightness.
Figure 7.2: The surface brightness profiles of the 8 brightest host galaxies. The hosts are fit in 2 dimensions with two models: an exponential disk, and an $R^{1/4}$ profile; both models are first convolved with the PSF before performing the fit. For the object image and the model images, we fit ellipses using the task *ellipse* in IRAF to obtain the surface brightness profiles shown above. The lines are not fits to the data points in these plots, but rather to surface brightness profiles of the best-fit model images. The solid line represents the exponential disk model, the dotted line the $R^{1/4}$, or de Vaucouleurs profile. See Table 7.1 for the parameter values of the best fit.
7.4 Central concentration and asymmetry

Abraham et al. (1996a) (see also Abraham et al. 1996b; Conselice et al. 2000a) have shown that galaxies can be roughly classified in three broad classes: E/S0, spiral, and peculiar/irregular/merging galaxies on the basis of their central concentration and asymmetry. The definition of the central concentration that we will use in this paper, following Bershady et al. (2000), is: 

\[ C = 5 \log_{10} \left( \frac{r_{80}}{r_{20}} \right) \]

where \( r_{80} \) (\( r_{20} \)) is defined as the radius that contains 80% (20%) of the galaxy light. A galaxy with a sharp profile, such as an elliptical, will show a relatively large value for the concentration parameter, while galaxies with a more gradual light profile, such as in spiral and irregular galaxies, will have a lower value. The asymmetry is determined by rotating a galaxy by 180°, and subtracting this rotated image off the original image. A perfectly symmetric galaxy will show no residuals in the difference image, while a galaxy with asymmetric features such as bright star-forming regions, or an interacting galaxy, will have large residuals. The absolute value of the pixels in the difference image, normalized by the pixel values in the original image, is a measure of the asymmetry parameter (Schade et al. 1995; Abraham et al. 1996b; Conselice et al. 2000a):

\[ A = \frac{\sum |I_o - I_\phi|}{2\sum |I_o|} \]

where \( I_o \) and \( I_\phi \) are the pixel intensities in the original and rotated image, respectively. Determination of the center of rotation is important. The asymmetry routine measures the asymmetries on a grid of centers around initial center value until a minimum asymmetry is found (within 5 pixels). In this paper we follow the method of Conselice et al. (2000a) for determination of the asymmetry.

Although this classification method is very promising, there are some caveats. One of these is that when observing high-redshift galaxies, one has to be careful with comparing these with their local counterparts because of bandshiftin effects: the rest-wavelength that is probed is bluer and therefore these galaxies will appear to be more asymmetric due to the dominant patchy younger population (e.g. Burgarella et al. 2001). From a multi-wavelength study of a small sample of nearby starburst galaxies, Conselice et al. (2000b) find that their overall morphology changes little from the visible to the ultra-violet (UV) wavelength regimes, suggesting that the inferred morphology of these starburst galaxies at high redshift would be similar to their local classification. Investigating the wavelength-dependent morphology of 34 nearby galaxies, Kuchinski et al. (2000) find that the change in apparent morphology from the visible to UV is dramatic for early-type spirals with prominent bulges, but modest for late-type spirals and irregulars. These results suggest that the change in inferred morphology with increasing redshift for GRB host galaxies, which on the basis of their star-formation rate are thought to be actively star-forming galaxies, should not be very large. On the other hand, Kuchinski et al.
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(2000) also find that starburst galaxies with centrally concentrated, symmetric bursts appear as ellipticals in the FUV; so these galaxies can disguise themselves.

We will use two galaxy samples with which we will compare the asymmetries and central concentrations of the GRB host galaxies. The first one is the BVI sum image of the Hubble Deep Field (HDF) (Williams et al. 1996), for which a visual classification is available of galaxies with magnitudes between $I=21$ and $I=25$ (Van den Bergh et al. 1996), as well as redshift information. We have performed two runs on the HDF: one with the full depth, in order to compare the concentration-asymmetry (C-A) values that we find with the visual classification of HDF galaxies. In another run we have degraded the HDF image to match the typical noise level of the images containing the GRB hosts. We did not rebin the images to match the pixel size of the STIS images ($0''0254$) with that of the HDF ($0''04$). For the second comparison sample we have used all the galaxies that are detected in the GRB host images. This second sample allows a direct comparison of the morphology of the hosts with that of an unbiased sample of galaxies that were imaged with the same pixel size, depth, and filter.

We use the SExtractor code (Bertin & Arnouts 1996) to detect objects on the images, and use these positions as input for our IRAF routines that calculate the asymmetry and concentration values. The images are first smoothed with a Gaussian function, after which we include objects in our catalog that have at least 3 contiguous pixels that are each $2\sigma$ above the sky background. For the full depth HDF we relax this condition to $10\sigma$, since we are not interested in the very faint objects. We also use SExtractor's star-galaxy separator index, or stellarity index, which ranges from 0 (definite galaxy) to 1 (definite star), to eliminate the stars. We set the threshold to 0.8. The remaining objects are checked for saturation, and put into the asymmetry and central concentration routines.

In Fig. 7.3 we plot a C-A diagram for the galaxies brighter than roughly $I=24$ in the HDF. As shown by Abraham et al. (1996a), galaxies of different Hubble types are located in different parts of this diagram. These broad bins can be roughly separated by the solid lines. The vertical line at an asymmetry value of 0.3 corresponds to the threshold above which local mergers are located. Fig. 7.4 shows the values that we find for 12 of the host galaxies compared to all the other galaxies detected in the same images (solid dots). As a second comparison we have added the B (F450), V (F606) and I (F814) images of the HDF to mimic the 50CCD response of STIS, in which most host galaxies were imaged. We add noise to this sum to scale it to the typical exposure time of the host galaxy images (exposure time ratio is roughly 25), and calculate the C-A values for the detected galaxies (crosses). The remaining 6 host galaxies of Fig. 7.1 are too faint to result in meaningful C and A values.

SExtractor will sometimes find several "centers" (peaks) for the same galaxy. For all the galaxies plotted in Fig. 7.4, for the degraded HDF image as well as the host-galaxy STIS
Figure 7.3: The concentration versus asymmetry for the galaxies brighter than $I=24$ in the HDF. The different symbols correspond to the broad Hubble type bins into which the galaxies were visually classified (by Richard Ellis in Van den Bergh et al. 1996): ellipticals are shown as filled circles, spirals as filled triangles, and peculiar galaxies as stars. Although there is some overlap, three different regions can be distinguished, which are separated by the solid lines. Local galaxies with an asymmetry larger than 0.3 tend to be mergers. The line separating the elliptical from the spiral region is a "best estimate" by eye.

and WFPC2 images, we verify if there is another peak present within a radius of 0''5. If so, we choose the peak with the lowest value for the asymmetry, and discard the other peak. We perform the same exercise for the host galaxies. For instance, for GRB991208 (see Fig. 7.1), SExtractor also picks up a peak eastward of the presumed host. Centering at this peak, the asymmetry routine measures a much larger asymmetry. The peak is closer than 0''5 from the host, and is therefore discarded. For the host of GRB000926 we assumed that the center of the galaxy is inbetween the two bright patches of emission (see Fig. 7.1). However, when adopting the center of the patch closest to the early afterglow position as the host galaxy center, we find values for the asymmetry ($A=0.36 \pm 0.10$) and central concentration ($C=4.1$) which are very similar to those of the host of GRB980613. The host of GRB990705 is the only one with contaminating foreground
7.5 Discussion

For the host of GRB 970508, Fruchter et al. (2000b) fitted exponential and de Vaucouleurs profiles, and found that the galaxy was best fit with an exponential disk with a scale length of 0\'046 ± 0\'006, and an ellipticity of 0.70 ± 0.07. We find almost the same result: the $\chi^2$ of the exponential disk profile is clearly lower (0.57 vs. 0.85 for the $R^{1/4}$ profile), and 0\'046 at the redshift of GRB 970508 corresponds to 0.38 kpc (assuming the cosmology mentioned above). The axis ratio that we find (0.39) corresponds to an
ellipticity of 0.61, which is also consistent with the result of Fruchter et al. (2000b).

For the entire sample of 8 bright hosts, however, the surface brightness profiles do not clearly distinguish between spiral galaxies and ellipticals as the morphological class of GRB host galaxies. As for the case of GRB 970508, the exponential profile clearly provides a better fit than the \( R^{1/4} \) profile for GRB 980703 and GRB 990712. But GRB 991208 and GRB 000418 are best fit with a de Vaucouleurs profile, although the difference is not so large in these cases. The scale lengths of the hosts range from very small: 0.14 kpc in the case of GRB 991208, to a value that is comparable to the Galactic scale length: 4.7 kpc for the host of GRB 990705.

As first shown by Abraham et al. (1996a), the values for the central concentration and asymmetry of a galaxy can be used as a rough indication for the morphology. In Fig. 7.3 we plot the C-A diagram for HDF galaxies brighter than roughly \( I = 24 \). Rough borders can be drawn between regions that are mainly occupied by ellipticals, spirals and irregular galaxies, although there is some overlap. With fainter magnitudes, this overlap increases. These regions are also shown in Fig. 7.4, where the C-A values for the host galaxies are plotted over two comparison samples: (1) the HDF image (sum of B, V and I) degraded in signal-to-noise (crosses), to mimic the typical exposure time of the GRB host galaxy images, and (2) all the galaxies present in the host galaxy images (solid dots). Both comparison samples occupy roughly the same regions in the C-A space, which suggests that GRB host galaxies are typical field galaxies. If GRBs would be drawn from regions with an overdensity of elliptical galaxies, for example in clusters, we would expect the sample of galaxies around the GRB hosts to be different from the HDF sample.

The GRB hosts do not all lie in a specific region of the diagram, but are rather scattered across most of the C-A parameter space. The majority of hosts have C-A values in the spiral region close to the “border” with the local merger population. For example, the host of GRB 990705 is clearly a “grand-design” late-type spiral (see Fig. 7.1), which is in agreement with its position in the C-A diagram. Two galaxies, those of GRB 980613 and GRB 010222, are located in the peculiar section. For GRB 980613 this is not unexpected, since its environment is very chaotic. For GRB 010222 this is less obvious, although for this galaxy a sub-mm flux is measured that is consistent with the host being a starburst galaxy. Starburst galaxies are likely to have a disturbed morphology, although this is not immediately clear from the image of this host.

The C-A values for three galaxies are consistent with these hosts having the morphological appearance of an elliptical. For one of these, GRB 000418, a very high star-formation rate has been inferred from sub-mm observations (as with the host of GRB 010222), which seems contradictory with its elliptical appearance. However, Kuchinski et al. (2000) found that starburst galaxies with a nuclear, symmetric burst, can have the morphological appearance of an elliptical. Assuming that GRBs are related to the deaths
of massive stars, and that nuclear starbursts mimic an elliptical appearance, we may expect the hosts of GRB 970508 and GRB 991208 to contain nuclear starbursts as well. In fact, the projected afterglow position of GRB 970508 is so close to the center of the galaxy, that Fruchter et al. (2000b) suggested that the burst may originate from such a nuclear starburst. The afterglow position for the other two galaxies in this region is also consistent with the center of the galaxy.

In conclusion, both from surface brightness profile fitting and by measuring the central concentration and asymmetry of a sample of GRB host galaxies, we find that these hosts do not fit into one clear single morphological class of galaxies. In the concentration-asymmetry diagram, most galaxies are consistent with being spirals or irregular galaxies, but three hosts are situated in the region occupied by ellipticals. If GRBs are associated with massive-star formation, for which there is increasing evidence, this supports previous observations that galaxies with different morphological appearances can be actively star-forming.

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