THE EXTINCTION TOWARD THE GRB 970228 FIELD

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ABSTRACT

We determine the local Galactic extinction toward the field of gamma-ray burst GRB 970228 using a variety of methods. We develop a maximum-likelihood method for measuring the extinction that compares galaxy counts in different bands in the field of interest to those in a field of known extinction, and we apply this method to the GRB 970228 field. We also measure the extinction by comparing the observed broadband colors of stars in the GRB 970228 field to the colors of library spectra of the same spectral type. Finally, we estimate the extinction using the neutral hydrogen column density and the amount of infrared dust emission toward this field. Combining the results of these methods, we find a best-fit Galactic extinction in the optical of $A_V = 1.09 \pm 0.20$, which implies that the intrinsic afterglow of GRB 970228 is significantly brighter and bluer than it appears.

Subject headings: dust, extinction — gamma rays: bursts

1. INTRODUCTION

GRB 970228 is the first gamma-ray burst (GRB) for which a counterpart at longer wavelengths has been detected. GRB 970228 was detected by the BeppoSAX satellite on 1997 February 28 (Costa et al. 1997a). BeppoSAX follow-up observations revealed a rapidly fading X-ray source (Costa et al. 1997b), and subsequent ASCA (Yoshida et al. 1997) and ROSAT (Frontera et al. 1997, 1998) observations showed that this source continued to fade over a 2 week period.

Ten days after the burst, Groot et al. (1997a) announced the detection of a fading source that was the first optical counterpart of a GRB. Frenetic activity followed, with previous observations being reanalyzed and new observations being taken, which led to reports of several detections in the optical and near-infrared (Groot et al. 1997b; Metzger et al. 1997a; van Paradijs et al. 1997; Metzger et al. 1997a; Klose, Stecklum, & Tufts 1997; Margon et al. 1997; Soifer et al. 1997; Metzger et al. 1997a; Pedichini et al. 1997; Djorgovski et al. 1997). Observations with the Hubble Space Telescope (HST) made another startling discovery. The fading GRB afterglow was spatially coincident with an extended source (Sahu et al. 1997a, 1997b; Fruchter et al. 1997).

In the first days of optical follow-up, the magnitudes of several nearby stars were reported. A star 2:9 west of the GRB served as a calibrating zero point for photometry and astrometry. It was referred to as "an early M-type dwarf" star, because of its observed colors, $V - I = 2.6$, and what were believed to be TiO features in a ESO 3.6 m spectrum (Groot et al. 1997b). However, when its spectrum was obtained with the Keck II telescope, it became clear that this star was actually "a mid K-type" star, showing "no evidence for the TiO bands reported" before (Tonry et al. 1997). The discrepancy indicated that the field was heavily extincted. Our inspection of the IRAS 100 μm map of the region showed that the direction toward the burst lies in a region of the sky showing both a strong gradient and clumping of the dust emission. These results motivated us to determine the optical extinction toward the GRB field in order to better understand the intrinsic properties of the burst afterglow. We reported our preliminary results in Castander & Lamb 1998. Here we present a complete description of our analysis and our final value for the local Galactic extinction. In a companion paper (Castander & Lamb 1999), we discuss the implications of our results for the properties of the burst afterglow and the nature of the extended optical source coincident with the GRB.

This paper is organized as follows. In § 2 we determine the extinction toward the GRB 970228 field by comparing galaxy number counts and colors using HST WFPC2 images of the GRB field and the Hubble Deep Field (HDF; Williams et al. 1996) and a maximum-likelihood method. In § 3 we measure the extinction using stellar spectral types and colors. In § 4 we estimate the extinction from measurements of the column density of hydrogen gas and dust emission measurements, using established correlations. We discuss our results in § 6 and present our conclusions in § 7.

2. EXTINCTION FROM GALAXY NUMBER COUNTS AND COLORS

Galaxy number counts can be used to directly measure the relative extinction between two fields. The idea is simple. The observed apparent optical magnitude of a galaxy is increased (the flux is decreased) because its radiation is absorbed by material, normally dust for optical extinction, along the line of sight. Because the number of observed galaxies increases with magnitude, number counts are reduced if extinction is present. Ignoring possible deviations due to galaxy clustering and sampling effects, in a given magnitude range and in a given filter, the number of galaxies should be the same irrespective of direction. Galaxy number counts are usually approximated as

$$N(m_1 < m < m_2) = C 10^{em},$$

where the values of the normalization, $C$, and the slope, $e$, depend on the specific filter and magnitude range. However, because of extinction, the observed apparent magnitude will be increased to $m_{obs} = m + A$. Therefore, if we compare two different fields with extinctions $A_1$ and $A_2$, their relative number counts in the same observed apparent magnitude

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range will be
\[
\frac{N_1(m_1 < m_{\text{obs}} < m_2)}{N_2(m_1 < m_{\text{obs}} < m_2)} = \frac{C_1}{C_2} \cdot 10^{\alpha_1(m + A_1) - \alpha_2(m + A_2)}.
\] (2)

If we measure the galaxy number counts in the same filter and in the same unextinguished apparent magnitude range, we can assume that the normalizations and slopes are the same. If we additionally assume that surface brightness dimming effects do not alter the relative number counts, then the ratio of the number counts depends only on the relative extinction and common slope:
\[
\frac{N_1(m_1 + A_1 < m_{\text{obs}} < m_2 + A_1)}{N_2(m_1 + A_2 < m_{\text{obs}} < m_2 + A_2)} = 10^{\alpha_1 A_1 - \alpha_2 A_2}.
\] (3)

In the present case, we wish to estimate the extinction toward GRB 970228 by comparing the number counts in two broadband filters of the HST WFPC2 observations of the GRB field and those of another field of known extinction. We have chosen the Hubble Deep Field (Williams et al. 1996) because it is the best-studied and deepest field for which the extinction is already known, having been observed with the same instrument and same filters.

The GRB 970228 field was observed by HST on 1997 March 26 and April 7. The optical counterpart was centered in the middle of the PC1 CCD in both observations, but there was a 2:40 difference in rotation angle between the two observations. At each epoch, four exposures were taken in the F606W filter and two exposures were taken in the F814W filter, totalling 4700 and 2400 s, respectively (Sahu et al. 1997c). The HDF was observed for 109,050 and 123,600 s in the F606W and F814W filters, respectively (for more details see Williams et al. 1996).

We retrieved the observations of both fields from the HST archive. After standard pipeline reduction, we combined the different exposures at each epoch of the GRB 970228 field using the IRAF/STSDAS task CRREJ. Then the combined second-epoch image was rotated and combined with the combined first-epoch image. The HDF images retrieved had already been processed and no further reduction was done.

We analyzed both fields using the same procedures, in order to reduce the systematic errors. We used the SEXTRACTOR image-analysis package (Bertin & Arnouts 1996) to automatically detect and measure object magnitudes. After generating catalogs of extracted objects and their magnitudes, all objects brighter than \( V_{606} = 26.5 \) and \( I_{814} = 25.9 \) were visually inspected and spurious objects were removed. This process was crucial in the F814W image of the GRB 970228 field because combining only four exposures precluded an accurate rejection of hot pixels. After generating the catalogs, we compared our galaxy number counts in the HDF with those obtained by the HDF team, in order to double-check our object-selection criteria and our magnitude measurements. The galaxy number counts in the two studies were consistent with each other in both filter images.

We determine the relative extinction between the two fields using a maximum-likelihood method. We construct a joint likelihood function that is the product of four likelihoods, each one being the likelihood that the galaxy catalog for a given image (GRB field or HDF) and filter \( (V_{606} \) or \( I_{814} \)), with its measured magnitudes and errors, resembles a power-law distribution (see eq. [1]) in a given magnitude range. This joint likelihood function contains eight parameters, the normalizations and slopes of the distribution in each of the four combinations of images and filters. If we analyze the catalogs in the same unextinguished apparent magnitude range (which requires us to know the extinction a priori; see eq. [3]), we can assume that the slopes are the same in the GRB 970228 field and the HDF in a given filter image:
\[
\begin{align*}
\alpha_{606}^{\text{GRB}} &= \alpha_{606}^{\text{HDF}}, \\
\alpha_{814}^{\text{GRB}} &= \alpha_{814}^{\text{HDF}} ;
\end{align*}
\] and that the normalizations are related;
\[
\begin{align*}
C_{606}^{\text{GRB}} &= C_{606}^{\text{HDF}} \cdot 10^{(A_{606}^{\text{HDF}} - A_{606}^{\text{GRB}})}, \\
C_{814}^{\text{GRB}} &= C_{814}^{\text{HDF}} \cdot 10^{(A_{814}^{\text{HDF}} - A_{814}^{\text{GRB}})}.
\end{align*}
\] (4)

If we further assume that the extinction behaves like the extinction law typical of the interstellar medium (Cardelli, Clayton, & Mathis 1987; O'Donnell 1994), we can relate \( A_{606} \) to \( A_{814} \) by integrating the extinction law over the filter responses,
\[
\begin{align*}
A_{606} &= 0.919 A_{V}, \\
A_{814} &= 0.608 A_{V}.
\end{align*}
\] (5)

With these assumptions, the joint likelihood function contains five parameters: two slopes, two normalizations, and the difference in the extinction between the two fields. Finally, marginalizing the likelihood function over both normalizations (F606W and F814W) and using the measured value of the extinction in the HDF field (\( A_{V} = 0 \); Williams et al. 1996) reduces the number of free parameters to three: \( A_{606} \), \( A_{814} \), and \( A_{V} \).

As explained above, we need to know a priori the value of the extinction in order to choose the magnitude ranges for which our reduction in the number of parameters is valid. Therefore, we proceed in the following iterative way. We start by choosing a value for the extinction (a good initial guess can be made by comparing the counts in different magnitude ranges). We then correct the observed magnitudes for that extinction value. Since the HDF has longer exposure times and therefore goes much deeper, we can find the extinction-corrected magnitude at which the GRB 970228 field counts begin to be incomplete by comparing them to the HDF counts. We adopt as our faint limiting magnitude the magnitude at which the cumulative counts in the GRB field fall below those in HDF by more than 10% in the F606W filter and 15% in the F814W filter (the number counts are smaller and the errors in the computed magnitudes are larger in the F814W filter, and that is why the deviation we allow is larger). We have checked this procedure by examining the probability as a function of the faint magnitude limit that the two extinction-corrected magnitude distributions are drawn from the same parent distribution, using the Kolmogorov-Smirnov (K-S) test. At our adopted faint magnitude limit, and taking into account our adopted bright magnitude limit as well, the hypothesis that the two count distributions come from the same parent distribution cannot be rejected with even 68% probability.

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2 All HST magnitudes quoted in this paper are in the AB magnitude system, unless otherwise stated by a subscript. Magnitudes in standard Johnson’s filters are in the Vega system.
Having determined the extinction-corrected faint magnitude limit, we take the corresponding non-extinction-corrected magnitude as the faintest limit to which we compute the joint likelihood function. We take as the bright magnitude limit the magnitude at which the number counts fall below \( \sim 7.5 \times 10^4 \) mag\(^{-1}\) deg\(^{-2}\) \((\sim 10\) objects per magnitude in the whole WFPC2 area\). We then maximize the likelihood function and obtain the best-fit values for the slopes and the extinction. Starting with this new value for the extinction, we iterate until the process converges.

It is worth noting that our final value for the extinction is almost independent of the bright magnitude limit that we adopt. The exact faint magnitude limit that we adopt does not affect the final value of extinction either, because we perform a correction for possible incompleteness a posteriori (see below).

Figure 1 shows our results. After a few iterations, we obtain values for the extinction and number counts slopes of \( A_V = 1.02 \pm 0.11 \), \( a_{606} = 0.41 \pm 0.1 \), and \( a_{814} = 0.36 \pm 0.1 \). The magnitude ranges used in the fit are \( 21.8 < V_{606} < 25.1 \), \( 22.72 < V_{\text{GRB}}^6 < 26.02 \), \( 21.0 < I_{\text{HDF}}^6 < 24.6 \), and \( 21.61 < I_{\text{GRB}}^6 < 25.21 \).

Our extinction estimate could be affected by clustering if one of the fields we have chosen to study is more or less strongly clustered compared to the other. The integral of the two-point angular correlation function gives an estimate of the additional variance in the number counts introduced by clustering (apart from the contribution to the variance due to number of galaxies used, which we have already taken into account in our maximum-likelihood method). In the magnitude ranges studied here, the two-point angular correlation function can be approximated by \( \alpha(\theta) \sim 0.80^{\theta-0.8} \) (Brainerd & Smail 1998). Integrating over the magnitude ranges used and the areas of the WF/C2 HST images studied, we find that the angular clustering on the sky adds a significant amount to the variance in the counts.

So far, we have neglected any possible effects introduced by the dimming of the surface brightness of the galaxies due to optical extinction. In the present case, the GRB field is considerably more obscured than the HDF, and therefore low surface brightness objects could be missed in the GRB field because they fall below the detection limit, even though they have magnitudes greater than the faint magnitude limit adopted. This would lead to an overestimation of the extinction. In order to correct for this effect, we have simulated WFPC2 images by degrading the WFPC2 HDF images using several values of the extinction, and then carried out the same analysis on these simulated images as we have done on the GRB field images. From these simulations, we conclude that, neglecting surface brightness effects, our maximum-likelihood procedure overestimates the amount of extinction by approximately 15%.

If we include the additional variance due to clustering in our maximum-likelihood method, and take into account the \( \sim 15\% \) correction due to surface brightness effects, we obtain a final extinction value of \( A_V = 0.89 \pm 0.18 \), where the estimated error includes the contribution from the clustering-modified maximum-likelihood method and that from the correction factor due to surface brightness effects.

3. EXTINCTION FROM STELLAR SPECTRAL TYPE VERSUS COLOR

As we remarked in § 1, the mislabeling of a mid-K--type star as an M-type star indicated that the GRB 970228 was heavily extincted, and provided the original motivation for the present study. In principle, the spectral type versus color of stars near the GRB on the sky provides the best and most secure means of determining the extinction toward GRB 970228, particularly if, as appears to be the case for the GRB 970228 field, the extinction varies on small angular scales.

We have therefore used publicly available spectra and photometry, as well as our own photometry, of two stars (denoted S1 and S2) that lie 2.9 west and 16.8 east of the GRB in order to measure the extinction toward GRB 970228. Unfortunately, as we shall see, the signal-to-noise ratios of the publicly available stellar spectra are insufficient to place narrow constraints on the spectral types of these two stars and therefore to accurately measure the extinction toward them.

Spectroscopy of the GRB optical afterglow was attempted by Tonry et al. (1997) using the Keck II telescope. Although they did not obtain a spectrum with a sufficient signal-to-noise ratio to discern the nature of the source, they obtained spectra of several other nearby objects that fell within the long slit that they used (see Fig. 2).

We retrieved the spectroscopic data from the Hawaii public FTP directory and reduced them. The observations had been taken with the Low-Resolution Imaging Spectrograph (LRIS) in six exposures on UT March 31.25 (500 and
Three stars were observed spectroscopically (two accidentally) with the Keck II telescope by Tonry et al. (1997) (Fig. 2). Among these three stars, star S3 is both fainter and farther away from the GRB than the other two, and we do not consider it further. Stars S1 and S2 are most likely dwarfs, since if they were giants their distances would have to be more than 100 kpc in order for their apparent magnitudes to be consistent with the absolute magnitude of K1v–K7v stars; for star S2, we obtain $A_V = 1.8_{-0.2}^{+0.4}$, with the best value again given by the fit to a K4v star and the range allowed corresponding to K1v–K7v stars; for star S2, we obtain $A_V = 1.5_{-0.4}^{+0.4}$, with the best value given by the fit to a K4v star and the range allowed corresponding to K2v–K5v stars.

The Keck II spectroscopic observations of the GRB field were taken at a mean air mass of 1.5 and at a position angle 12° away from the parallactic angle. Although the deviation from the parallactic angle is small, the relatively high air mass makes it uncertain whether the stellar spectra can be flux-calibrated accurately enough to obtain a precise optical-extinction measurement. Therefore, we have not included the extinction values found above in our final determination of the extinction toward the GRB 970228 field. Instead, we have opted to use the stellar spectra only to assign spectral types to the stars, and to use photometric data to obtain the optical extinction (see below).

Stars S1 and S2 lie in the HST WFPC2 images of the GRB 970228 field. Our reduction procedure to obtain magnitudes and accurate errors differs slightly from the method
described in § 2. The main differences are that we did not combine the two sets of images in the same filter and did a more careful propagation of the errors involved to obtain a magnitude. A detailed description of our methodology is given in Castander & Lamb (1998). Table 1 lists our measurements.

We also observed the GRB 970228 field with the Astrophysical Research Consortium 3.5 m telescope at Apache Point Observatory. The field was imaged in photometric conditions for 1800 s in the $B$-band filter and 1200 s in the $V$-band filter using the Seaver Prototype Imaging camera (SPIcam) on 1998 November 22. These images were debiased and flat-fielded using standard IRAF routines. The magnitude for stars S1 and S2 were obtained by fitting their flux profiles to the point-spread function (PSF) determined from eight bright stars. The photometric calibration was carried out using three different Landolt fields (Landolt 1992a, 1992b), with approximately six standard stars each, observed at several air masses. Table 1 presents our measurements. Unfortunately, our GRB 970228 images were not deep enough to allow a measurement of star S3. Moreover, we only detected star S1 at the 2.5 σ level in the $B$ band; therefore, we have also not used star S1 in our determination of the extinction toward the GRB.

Once we have photometric information in four optical bands and a spectral type classification, we can determine the optical extinction necessary to produce the observed counts from a star of such a spectral type. We proceed in the following manner. We first redden and normalize a template library spectrum to obtain the expected counts in the four bandpasses used, taking into account the appropriate zero points to convert from fluxes to counts. We then determine the best-fitting extinction value for that template by minimizing the $\chi^2$ of the predicted counts compared to the observed counts with their errors. Finally, we repeat this procedure for all allowed spectral types (see § 3). We quote as our best extinction value the one obtained using a K4V star, for which the $\chi^2$ minimization gives the following best-fit values: $A_V = 1.44, B = 23.10 (1011 e^-), V = 21.76 (3677 e^-)$, $(V_{606}) = 21.69 (133606 e^-)$ and $(I_{814}) = 21.48 (62391 e^-)$. Utilizing spectral types from K2V to K5V–K7V, we obtain $A_V = 1.44^{+0.15}_{-0.05}$.

### 4. EXTINCTION FROM NEUTRAL HYDROGEN COLUMN DENSITY

*BeppoSAX* detected the GRB 970228 afterglow in X-rays with both the Medium-Energy Concentrator Spectrometer (MECS) and Low-Energy Concentrator Spectrometer (LECS) instruments (Costa et al. 1997b). In the first set of observations, 8 hr after the burst, the measured flux was bright enough to fit a spectrum to the measured counts in the 0.1–10 keV energy band. The best fit was obtained for a power-law spectrum with photoelectric absorption of $N_H = 3.5^{+3.3}_{-2.3} \times 10^{21}$ cm$^{-2}$ (Frontera et al. 1998). Converting this value to color excess (see below), and assuming that all of the absorption is due to our own Galaxy, would imply a color excess of $E(B-V) = 0.73^{+0.69}_{-0.48}$ and an optical extinction of $A_V = 2.26^{+1.13}_{-1.48}$.

Searching published H I surveys, we find values for the neutral hydrogen column density of $1.60 \times 10^{21}$ and $1.59 \times 10^{21}$ cm$^{-2}$ from Stark et al. (1992) andDickey & Lockman (1990), respectively. Adopting the conversion

![Hydrogen column density](image1.png)

![IRAS 100 μm map](image2.png)

**Fig. 3.**—Hydrogen column density (left) and IRAS 100 μm (right) maps. Both are 8.5′ × 8.5′. Their resolutions are ~ 1" and ~ 5′, respectively. The white circle (40′′ diameter) is centered on the position of the GRB 970228 optical transient. The bright regions correspond to strong emission, the dark regions to weak emission. North is up and east is to the left on both images. A strong emission gradient is noticeable in the GRB 970228 region.
factor between H $^\text{I}$ and color excess of $4.8 \times 10^{21}$ cm$^{-2}$ mag$^{-1}$ (Bohlin, Savage, & Drake 1978), we obtain $E(B - V) = 0.33 \pm 0.13$. If instead we adopt the calibration of Heiles (1976), for which the author gives errors, a value of neutral hydrogen column density of $1.60 \times 10^{21}$ cm$^{-2}$ would yield a color excess of $E(B - V) = 0.29 \pm 0.03$. The difference between these two values is due to a zero-point difference in the relation.

Other methods of determining the color excess give slightly different values. For example, Burstein & Heiles (1982), using a combined H $^\text{I}$ column density/galaxy number counts method, get a value of $E(B - V) = 0.23$. However, the hydrogen column density value used by Burstein & Heiles has been superseded by more precise measurements. Using instead the hydrogen column density value of Stark (1992) and Dickey & Lockman (1990), we would obtain $E(B - V) = 0.25 \pm 0.09$, with the Burstein & Heiles (1982) calibration.

The error in the neutral hydrogen column density measurement is negligible compared to the error in its relation to reddening, and therefore should not add significant uncertainty to the color-excess value derived. However, the resolution of the H $^\text{I}$ maps is poor, around $1^\circ$ or $2^\circ$. The Dickey & Lockman (1990) 21 cm H $^\text{I}$ map of the GRB 970228 field is shown in Figure 3. As can be seen, the GRB 970228 is in a region showing a relatively steep H $^\text{I}$ gradient on angular scales of a few degrees, and it is quite conceivable that there are significant deviations on small angular scales from the value assumed.

Taking into account these considerations, we conservatively adopt a value of $E(B - V) = 0.30 \pm 0.13$. Assuming an extinction law typical of the diffuse interstellar medium, $R_V \equiv A_V/E(B - V) = 3.1$ (Cardelli et al. 1987; O'Donnell 1994), this gives an extinction value of $A_V = 0.93 \pm 0.39$.

5. EXTINCTION FROM INFRARED EMISSION

The optical extinction is also known to correlate with infrared emission at long wavelengths ($\sim 100 \mu$m). However, this correlation shows substantial scatter because the infrared emission is dependent on the radiation field and the temperature of the dust grains (e.g., Bouvier & Pérault 1988). The IRAS 100 $\mu$m emission map of the area is shown in Figure 3. The 100 $\mu$m infrared emission toward GRB 970228 is $I_{100 \mu m} = 13.1$ MJy sr$^{-1}$. Rowan-Robinson et al. (1991) give a conversion factor between visual extinction and dust emission of $A_V/I_{100 \mu m} = 0.06$ mag MJy$^{-1}$ sr$^{-1}$, which was computed by modeling the interstellar grains and their response to the interstellar radiation field. This relation should be valid to within approximately $30\%$. Thus, we obtain a value for the extinction of $A_V = 0.79 \pm 0.21$.

Recently, Schlegel, Finkbeiner, & Davis (1998; hereafter SFD98) published reddening estimates based on COBE DIRBE and IRAS infrared dust emission measures. They find a value for the GRB 970228 direction of $A_V = 0.70 \pm 0.16$, consistent with Burstein & Heiles (1982) and the IRAS 100 $\mu$m emission with the Rowan-Robinson et al. (1991) conversion factor.

6. DISCUSSION

We have determined the Galactic extinction toward GRB 970228 using several different methods. First, we have measured the distribution of galaxy magnitudes in the HST WFPC2 images in two different filters of the GRB field and compared them to the same quantities in images of the HDF, a field of known optical extinction. In order to reduce the systematic errors, we reanalyzed the HDF using the same techniques that we used for the GRB field. Our object catalog for the HDF is very similar to that of the HDF team, reinforcing the view that our selection method and magnitude determination are appropriate. We also checked all selected objects in the magnitude ranges studied to make sure that the different depths of the images had not influenced the number counts, as could be the case, for example, with the deblending algorithm. Another possible source of error is misidentification of stars as galaxies. Objects in the GRB field are detected at a lower signal-to-noise ratio than are objects in the same magnitude range in the HDF, and they are therefore more difficult to classify. Moreover, the GRB field lies at a much lower Galactic latitude, increasing the surface number density of stars. Although the number of stars detected and rejected is low, and therefore the statistics on them are poor, we have checked that the number of stars detected is compatible with the expectations of the Bahcall & Soneira (1984) Galactic model for this particular Galactic latitude. As a worst-case scenario, we estimated the extinction with our maximum-likelihood method, assuming that all objects were galaxies. In this extreme case, the value of $A_V$ that we obtain is approximately 0.1 mag lower than our best estimate.

Two other possible concerns are the effect of galaxy clustering due to large-scale structure, and the effect that the extinction itself can have on low surface brightness objects. The GRB field shows considerably more extinction than does the HDF, and it was exposed for a much shorter time. Assigning fainter magnitudes to low surface brightness objects in the GRB field, or missing them altogether, would lead to an overestimation of the extinction. We believe that we have adequately taken these effects into account by using an extinction-corrected maximum-likelihood method, and by applying a correction factor for the effects of surface brightness that we derived from simulations (see §2).

In our maximum-likelihood analysis, we assumed an extinction law and combined the F606W and F814W images. If we analyze the two images separately, we obtain results that are consistent with each other, although the errors are larger. The F814W image gives a value of $A_V$ that is somewhat higher than that given by the F606W image, as can be seen in Figure 1. The $A_V$ given by the combined maximum-likelihood method is closer to that given by the F606W image than to that given by the F814W image. This is because the F606W observations, having approximately double the exposure time, go deeper. Consequently, more objects are detected in the observations taken in this filter, and it has more weight in the combined maximum-likelihood method.

We have also measured the optical extinction by analyzing the spectra of two nearby stars. The spectra of these stars should, in principle, give the best estimate of the extinction toward the GRB, because they lie close to the GRB on the sky and sample a wide wavelengths range ($\sim 4500$–$8000$ A). We obtained estimates of $A_V$ using the Keck II stellar spectra themselves. The values obtained are larger than that obtained using galaxy counts. However, the spectra were taken at a relatively high air mass, with the slit oriented at an angle $12^\circ$ away from the parallactic angle. Consequently, we have not used these values in our final determination of the extinction toward GRB 970228.
Our stellar photometry of stars S1 and S2 also samples a wide wavelength range, from the B to the I filter (\(\sim 4500\)–8000 \(\AA\)). However, the signal-to-noise ratio of our measurement of the B-band magnitude of star S1 is low; consequently, we do not use star S1 in our determination of \(A_V\). The main contribution in our error budget for the value of \(A_V\) that we determine from our photometry of star S2 is the allowed range of spectral types. The error due to our photometric measurements is considerably smaller. In particular, the \(V_{606}\) and \(I_{814}\) magnitudes are very well constrained and carry a larger weight in the \(\chi^2\) minimization. Thus, this method, which is potentially superior to the others, is hampered by the low signal-to-noise ratio of the stellar spectra and the B-band magnitude of star S1. 

The other methods we have used do not measure the extinction in the optical directly, but rely on correlations between various observed quantities and the optical extinction to estimate \(A_V\). This renders these techniques more uncertain. The correlation between hydrogen column density and color excess (or extinction), and between the infrared 100 \(\mu\)m emission and color excess are known to have large intrinsic scatters (e.g., Bohlin et al. 1978; Bouvier & Préal 1988). The infrared emission has the additional disadvantage that, near the Galactic plane, the contribution of the stellar radiation field to the dust emission declines with distance from the Galactic center (Rowan-Robinson et al. 1991). GRB 970228 is located in the direction of the Galactic anticenter at \(l = 189.913, b = -17.941\), and it is possible that the relation we have used to obtain \(A_V\) underestimates it. On the other hand, the value obtained by SDF98 is very similar and is based on a different calibration that does not depend on this correlation, so the effect of Galactic longitude is unclear. Another concern in these methods is spatial resolution. The resolution of the hydrogen column density maps that we have used is \(\sim 1^\circ\), while the resolution of the IRAS 100 \(\mu\)m maps that we have used is \(\sim 5'\). The two maps correlate well on large angular scales. However, the resolution of the hydrogen column density map is clearly insufficient for a good determination of the extinction toward GRB 970228, because there is a strong gradient in this region. The IRAS 100 \(\mu\)m image, with its higher resolution, demonstrates this point: structures of a few arcminutes in size that are visible in the 100 \(\mu\)m map are smeared out in the H I image. The direction of GRB 970228 coincides with the outskirts of a supernova remnant (SNR) centered \(\sim 10'\) to the east (left) outside of the image shown in Figure 3. While the IRAS 100 \(\mu\)m map suggests that material from this SNR does not contribute to the extinction in the GRB field, the map does not have enough resolution to provide a definitive conclusion.

Table 2 summarizes our measurements. We compute our best value for the optical extinction with the weighted average of the values obtained by the different methods. We apply two weights to average our measurements. One is inversely proportional to the relative error, and the other is based on our subjective evaluation of the method reliability. We arbitrarily assign a 3 times larger weight to methods based on optical data than to those based on other wavelengths. These weights are tabulated in columns (3) and (4) of Table 2.

The method based on stellar spectra and colors gives a higher value for the extinction than do the other methods. However, it is consistent, within the errors, with the other methods, except for the SDF98 infrared-emission method. If we were to use the 100 \(\mu\)m infrared emission–optical extinction relation of Rowan-Robinson et al. (1991) instead, the extinction inferred from the dust infrared emission would be marginally consistent with that given by the stellar method. Have we overestimated the extinction using star S2? If we have misclassified it, assigning to it an earlier spectral type than it actually is, this would lead to an overestimation of \(A_V\). We believe, however, that we have been very cautious in assigning the range of possible spectral types of this star (see § 3), which leads to the large errors quoted. For example, if the real value of the extinction is \(A_V \sim 0.9\), S2 would have to be at least a K7\(v\) star in order to be compatible with the observed colors. The lack of any sign of even weak molecular features in the spectrum rules this out. A photometric error could also give a higher (or lower) value of the extinction. For a K4\(v\) star, our best-fit spectral type, a value for the extinction of \(A_V \sim 0.9\) would imply a \(V_{606} - I_{814}\) color 0.16 mag bluer than the value we measure. This would require that the real color lie 10 \(\sigma\) away from the value we measure, something we think is highly unlikely, given that we measure the same color for S2 in the March 26 and in the April 7 images.

If our determination using star S2 is correct, then the extinction toward GRB 970228 is at least \(A_V \sim 1.0\), and probably larger. Why do the other methods give somewhat lower values? We believe that a plausible explanation is variations in the extinction on angular scales \(<1'\). The IRAS 100 \(\mu\)m map shows evidence of strong variations in dust emission on scales of a few arcminutes, which is the map’s angular resolution (Fig. 3). It is therefore likely that

| Method                  | \(A_V\)      | Weight 1 | Weight 2 |
|------------------------|--------------|----------|----------|
| Number Counts          | 0.89 ± 0.18  | 0.30     | 0.375    |
| Star S2                | 1.44 ± 0.15  | 0.291    | 0.375    |
| X-ray extinction       | \(<2.26 ± 0.48\) | 0.000 | 0.000 |
| N(H I)                 | 0.93 ± 0.39  | 0.144    | 0.125    |
| \(I_{100\mu m}\) (correlation) | 0.79 ± 0.21 | 0.000 | 0.000 |
| \(I_{100\mu m}\) (SDF98) | 0.70 ± 0.16 | 0.265 | 0.125 |
| Combined (weight 1)    | 1.01 ± 0.10  | 0.45     | 0.20     |
| Combined (weights 1 and 2) | 1.09 ± 0.20 | 0.45     | 0.20     |
the difference between the values of $A_V$ derived from hydrogen and infrared dust emissions and that obtained from the color of the nearby star S2 is due to variations in the extinction on arcminute scales. In order to explain the difference between the extinction estimates obtained from galaxy number counts and the color on the other hand, the extinction would have to vary on scales of less than 1', because the WFPC2 images cover angular scales of $\approx 1'$, while star S2 lies only 16.8' away from GRB 970228. Some support for this hypothesis comes from star S1, which lies only 2.9' away from GRB 970228. Although not used in our determination of the extinction, this star gives a value for $A_V$ that is similar to that given by star S2.

González, Fruchter, & Dirsch (1999) have also investigated the extinction in the GRB 970228 field. They compare galaxy number counts and colors in the GRB 970228 field to those in several other HST WFPC2 images in order to obtain a value for $A_V$. They obtain a value that is consistent with the SFD98 estimate. Fruchter et al. (1999), revisiting this work and adding new extinction estimates, adopt a value of $A_V = 0.8 \pm 0.2$ for the GRB 970228 field. Fruchter et al.’s best-fit value differs from ours, but the uncertainties in the two determinations overlap.

7. CONCLUSIONS

We have determined the extinction toward the field of GRB 970228, using the relative number counts between the WFPC2 images of the HDF and GRB 970228 fields in two filters and the spectra versus colors of two nearby stars, S1 and S2. The first method gives a relatively accurate value of the extinction on angular scales of 1', but cannot be extended to smaller angular scales because of the smaller number of galaxies detected and the increasing variance in the number of galaxies detected due to clustering. The second method is, in principle, the best and most secure way of determining the extinction toward GRB 970228, because the two stars lie near the GRB on the sky and the photometry covers a wider spectral range. However, the accuracy of the determination is hampered by the low signal-to-noise ratio and nonoptimal coverage of the spectra, which makes spectral classification somewhat uncertain, and the low signal-to-noise ratio of the B-band magnitude of the star S1. We have used other indirect methods based on the hydrogen column density and the dust 100 $\mu$m emission.

Combining the above techniques, and weighting the optical methods more than the other, indirect ones, we obtain a best value of $A_V = 1.09^{+0.10}_{-0.12}$ for the local Galactic extinction in the direction of GRB 970228. The differences between the values of $A_V$ obtained using the different methods may indicate that the extinction in this direction varies on small angular scales. The value of $A_V$ that we find implies that the afterglow of GRB 970228 is intrinsically brighter and bluer than it appears. For example, in the $R_c$ filter the intrinsic magnitude is 0.9 brighter and the intrinsic $V - I_c$ color is 0.45 mag bluer than observed.

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