The Galactic Extinction Toward GRB 970228 and Its Implications

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Abstract. The IRAS 100 micron image of the GRB 970228 field shows that the amount of galactic dust in this direction is substantial and varies on arcminute angular scales. From an analysis of the observed surface density of galaxies in the 2.6′ × 2.6′ HST WFPC image of the GRB 970228 field, we find $A_V = 1.1 \pm 0.10$. From an analysis of the observed spectra of three stars in the GRB 970228 field, we find $A_V = 1.71^{+0.20}_{-0.40}$. This value may represent the best estimate of the extinction in the direction of GRB 970228, since these three stars lie only 2.7″, 16″, and 42″ away from the optical transient. If instead we combine the two results, we obtain a conservative value $A_V = 1.3 \pm 0.2$. This value is significantly larger than the values $A_V = 0.4 – 0.8$ used in papers to date. The value of $A_V$ that we find implies that, if the extended source in the burst error circle is extragalactic and therefore lies beyond the dust in our own galaxy, its optical spectrum is very blue: its observed color $(V - I)_\text{obs} \approx 0.65^{+0.74}_{-0.94}$ is consistent only with a starburst galaxy, an irregular galaxy at $z > 1.5$, or a spiral galaxy at $z > 2$. On the other hand, its observed color and surface brightness $\mu_V \approx 24.5$ arcsec$^{-2}$ are similar to those expected for the reflected light from a dust cloud in our own galaxy, if the cloud lies in front of most of the dust in this direction.

INTRODUCTION

The IRAS 100 micron image of the GRB 970228 field shows that the amount of galactic dust in this direction is substantial and varies significantly on arcminute angular scales (see Figure 1). Here we report a determination of the visual extinction $A_V$ toward GRB 970228 using two methods: (1) the observed versus the expected surface density of galaxies in the HST WFPC 606 and 814 nm images of the GRB 970228 field; and (2) the observed color versus the spectral type of three stars that lie near the position of the optical transient (see Figure 2).

ANALYSIS AND RESULTS

Galaxy number counts can be used to measure directly the relative extinction between two fields. Since absorption due to dust increases the observed apparent magnitude of a galaxy at infrared, optical, and ultraviolet wavelengths, the number
FIGURE 1. IRAS 100 µm map of the GRB 970228 field, covering 8.5° × 8.5° and having a resolution of 2'. The bright regions correspond to strong dust emission, the dark regions to weak dust emission. We have superposed on the map a circle 20' in radius, centered on the position of the optical transient (R.A. = 5h01m46.7s, Decl. = +11°46'54""J2000).

of galaxies per unit area brighter than a given apparent magnitude is reduced if extinction is present. We have compared the surface density of galaxies as a function of apparent magnitude in the HST WFPC 606 and 814 nm images of the GRB 970228 field [1] with similar images of the Hubble Deep Field [2] (HDF) (Figure 3). We have used the same procedure to analyze both fields; our results for the HDF field agree with those reported earlier [2]. We restrict our comparison to galaxies in the WFPC 606 and 814 nm images of the GRB 970228 field for which V_{606} ≤ 26.0 and I_{814} ≤ 25.2, apparent magnitudes for which the galaxy counts in this field are complete.

We determine the extinction in the HST WFPC images of the GRB 970228 field using a maximum likelihood method. We construct a likelihood function that is a product of four individual likelihood functions, one for the 606 and 814 nm images of each field. We model the surface density of galaxies as a function of apparent magnitude in each image as a power-law distribution. We assume that the slopes α_{606} and α_{814} of the power-law distributions in the 606 and 814 nm images are the same in the GRB 970228 field and HDF. We further assume that the extinction
in both fields is described by the typical extinction behavior of the interstellar medium, so that $A_{606} = 0.92A_V$ and $A_{814} = 0.61A_V$. The resulting likelihood function only depends on five parameters: the normalizations and the slopes $\alpha_{606}$ and $\alpha_{814}$ of the power-law distributions in the two filters and the difference in the extinction between the GRB 970228 field and the HDF. We then marginalize this likelihood function over the normalizations in the 606 nm and 814 nm filters and use the measured value $A_V^{HDF} = 0.0$ [2]. This reduces the number of parameters to three: $\alpha_{606}$, $\alpha_{814}$, and $A_V$. Maximizing the likelihood of the observed surface density of galaxies as a function of apparent magnitude in each image of each field, given the model, we obtain a best-fit value $A_V = 1.1 \pm 0.10$.

We also determine the visual extinction $A_V$ toward GRB 970228 using the spectra of three stars, denoted S1, S2, and S3, that lie near the optical transient in the GRB 970228 error circle (see Figure 2). The spectra of these stars were obtained on 1997 March 31, April 1, and April 2 UT using the LRIS spectrograph on the Keck II 10-meter telescope [3,4]. Comparing the observed spectra with the stellar spectral atlases [5,6], we find that S1, S2, and S3 lie in the spectral ranges K3v-K5v, K4v-K7v, and M0v-M3v, respectively. Reddening the spectra in the stellar spectral atlases, we obtain best-fit spectra and visual extinction values for S1, S2, and S3 of $A_V = 1.4^{+0.5}_{-0.3}$, K4v and $A_V = 1.8^{+0.5}_{-0.3}$, and M2v and $A_V = 1.8^{+0.5}_{-1.0}$, respectively. Weighting the individual values of $A_V$ by the signal-to-noise of their spectra, we obtain a combined value $A_V = 1.71^{+0.20}_{-0.40}$. This may represent the best estimate of the extinction in the direction of GRB 970228, since these three stars lie only 2.7", 16", and 42" away from the position of the optical transient.

Combining the results of our analysis of the surface density of galaxies in the GRB 970228 field and the results of our analysis of the spectra of stars S1, S2, and S3, we obtain a conservative value $A_V = 1.3 \pm 0.2$. This value is consistent with the X-ray spectrum of the gamma-ray burst itself, which yields $n_H = 3.5^{+3.3}_{-2.3} \times 10^{21}$
From an analysis of the observed surface density of galaxies in the $2.6' \times 2.6'$ HST WFPC image of the GRB 970228 field, we find $A_V = 1.1 \pm 0.10$. From an analysis of the observed spectra of three stars in the GRB 970228 field, we find $A_V = 1.71^{+0.20}_{-0.40}$. This value may represent the best estimate of the extinction in the direction of GRB 970228, since these three stars lie only 2.7'', 16'', and 42'' away from the optical transient. If instead we combine the two results, we obtain a conservative value $A_V = 1.3 \pm 0.2$.

This value is significantly larger than the values $A_V = 0.4 - 0.8$ used in papers to
FIGURE 4. Expected colors for several kinds of galaxies at different ages as a function of redshift \( z \). The curves include the appropriate K-correction, but assume no galaxy evolution. The thick solid line shows \((V - I_c)_{\text{obs}}\) for the extended source in the burst error circle; the hatched region indicates the range of uncertainty in this color. This figure shows that the extended source is very blue: its \( V - I_c \) color is consistent only with that expected for starburst galaxies, for irregular galaxies at \( z > 1.5 \), or for spiral galaxies at \( z > 2 \).

date. The value of \( A_V \) that we find implies that, if the extended source in the burst error circle is extragalactic, its optical spectrum is very blue: its observed color of \((V - I_c)_{\text{obs}} \approx 0.65^{-0.74} \) is consistent only with a starburst galaxy, an irregular galaxy at \( z > 1.5 \), or a spiral galaxy at \( z > 2 \), after taking into account the measured extinction. On the other hand, its observed color and surface brightness \( \mu_V \approx 24.5 \) arcsec\(^{-2} \) are similar to those expected for the reflected light from a dust cloud in our own galaxy, if the cloud lies in front of most of the dust in this direction.

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