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DEEP OPTICAL COUNTERPART SEARCHES OF GAMMA-RAY BURST LOCALIZATIONS

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ABSTRACT

We report the results of a 5 year CCD imaging program of small gamma-ray burst (GRB) error boxes from the First Interplanetary Network and an optical transient field. The fields include GBS 0010–16, GBS 0552–08, GBS 1028+46, GBS 1205+23, GBS 1412+79, OTS 1809+31, GBS 2006–22, and GBS 2252–03. A total of 274 hours of open shutter time was used to obtain multiple *UBVI*-filtered frames covering an area approximately twice that of the 99% confidence localizations. For 2070 objects in these fields above the survey detection limit of $V \approx 24$, 79,000 calibrated photometric measurements were made. The objectives of the survey were to search for objects of unusual colors, variability, or proper motions. The final census of objects in these fields is consistent with the expected numbers of normal stars, galaxies, and proper motion objects based on statistics of large-scale surveys. While no obvious GRB optical counterparts were found, several potentially interesting objects were discovered, along with marginal evidence for a QSO excess at the rate of one per high Galactic latitude localization. The results and implications are discussed in detail along with suggestions for future work.

Subject headings: gamma rays: bursts — quasars: general — surveys — techniques: photometric

1. INTRODUCTION

The origin of classical cosmic gamma-ray bursts (GRBs) continues to be one of astronomy's most enigmatic problems, despite their having been discovered more than 20 years ago (Klebesadel et al. 1973). With a discovery rate of approximately 0.8 events per day by the BATSE experiment on board the *Compton Gamma-Ray Observatory* (Fishman et al. 1994), more than 700 GRB events have now been cataloged by that device alone (Meegan et al. 1994). Despite this, no observational or theoretical evidence has yet been presented which provides a conclusive demonstration of their ultimate nature. For many years, models of activity near the surfaces of highly magnetized Galactic neutron stars were favored, since in these models production of gamma-ray bursts were fairly easy to envision (see Higdon & Lingenfelter 1990, and references therein). However, results from BATSE have shown (1) a highly isotropic distribution of source locations and (2) a relative paucity of fainter GRB events (Fishman et al. 1994; Meegan et al. 1994) indicating that GRBs come from a uniformly filled but bounded volume of space. These results have thus called into question Galactic neutron star models. Even models invoking highly extended Galactic halos now appear to be ruled out due to the lack of excess events toward nearby galaxies (see Hartmann 1994; Hakkila et al. 1994). Evidence for time dilation in GRB pulse profiles (Norris et al. 1994) is consistent with extragalactic GRBs, although noncosmological explanations may also be possible (Band 1994). On the other hand, Quashnock & Lamb (1993, 1994) argue that a significant fraction of GRBs may have repeated, a result wholly inconsistent with the timescale thought appropriate for one cosmological source model—neutron star mergers in external

galaxies. These controversies are reviewed, for example, by Hartmann et al. (1994) and Schaefer (1994). Although this is not the place for a comprehensive review of even the most recent literature, it can be safely stated that, despite the impressive efforts in theory and the large amount of data now available directly from GRB events, their ultimate origins are still a largely open question.

Whether GRB events originate at Galactic or cosmological distances, the identification of radiation at other than gamma-ray wavelengths associated with a GRB event would be an important breakthrough in understanding the GRB phenomenon. Searches at optical wavelengths can be separated into strategies designed to detect light associated with the burst itself and strategies designed to detect a quiescent component. The former involve either all-sky monitoring (see Vanderspek, Krimm, & Ricker 1994; Greiner et al. 1994) or telescopes with rapid response capability (see Bonnell et al. 1994; Barthelmy et al. 1994b). No optical transient (OT) associated with a GRB event has yet been discovered by these techniques which are currently limited by relatively bright detection limits and/or long response times to the GRB location, and the UV atmospheric spectral cutoff. The apparent magnitude and response time limitations may soon be improving, however, as described by Hudec & Soldán (1994), Barthelmy et al. (1994a), and Pedersen, Andersen, & Boer (1994).

A third method involves the inspection of archival photographic plates in the direction of GRB localizations in the hope of finding non-time-correlated OT events. While this method has suffered from plate defects which can mimic OTs (see Zytzkow 1990; Greiner, Wenzel, & Degel 1990; Schaefer 1990), there is now little doubt about the reality of several of these events

(Greiner 1992; Hudec et al. 1995). If associated with GRBs, the short time between OT and GRB events (< 100 yr) may favor a Galactic GRB origin, although repetitive extragalactic activity can also occur. However, whether the known OTs are associated with GRBs is an open question. The recent discovery by Hudec et al. (1995) of a highly likely OT near, but outside the gamma-ray localization of GB 910219, and the subsequent discovery by Vrba et al. (1994) of a QSO at the position of the OT, is a case in point. Vrba et al. (1994) discuss some of the physical consequences of possible OT/GRB/QSO associations. Whether or not OT flashes are ultimately found to be associated with the GRB phenomenon, there is as yet no compelling evidence for the association of an OT with a GRB event.

The alternative to the above techniques is to search for radiation coming from the quiescent source underlying the GRB. All GRB models, whether Galactic or cosmological, predict underlying sources which are unlike normal stars and, thus, may be discernable by distinctive properties such as unusual colors or variability (e.g., neutron stars, AGNs, QSOs). While a number of studies have made some attempts at surveying GRB localizations (see Table 1, described below), none of these have provided comprehensive data capable of systematic, long-term study of faint objects. Thus, in 1987 we initiated a 5 year, deep CCD imaging survey of a number of small GRB localizations aimed at providing magnitudes, colors, variability statistics, and proper motion data on objects as faint as 24th magnitude. The results of this program are described in this paper.

2. OBSERVATIONS

2.1. Survey Strategy

At the time of the beginning of this survey, several optical studies of GRB error boxes had already been completed (see Table 1 below) without having discovered any obvious optical counterpart candidates. Hence, it was clear, that in order to make this survey useful, we would have to expand observational parameter space greatly over that which had been done before. In particular, we wished to explore properties of objects in the GRB error boxes that could only be examined with long-term synoptic observations such as quiescent-level variability, flashes, and proper motions. In order to carry out such a program in a systematic fashion the following strategies were adopted:

1. For the GRB localizations studied, the entire 99% confidence level error boxes would be surveyed along with as much external area as practical.
2. Each box would be surveyed to the practical light detection limit of a 1.0 m telescope; assumed a priori to be ≈ 24 mag for the V filter.
3. Obtain repeated V and I filter photometry over a period of 5 years to study variability and proper motions.
4. Obtain additional deep U and B filter photometry to extend the wavelength baseline for color data.
5. Obtain photometry of every object on every frame down to the detection limit.
6. Examine each frame for unexpected images due to variability of objects normally below the detection limit in their quiescent state.
7. On the basis of the above observations determine which objects in or near each GRB error box have variability, color, or proper motion properties beyond those expected for various classes celestial objects, e.g., stars, galaxies, QSOs, etc.

8. Determine the population of extragalactic objects in each field based on either morphological or color data.

9. Compare the final census of Galactic and extragalactic objects to that expected at the given Galactic latitude and survey faintness limit for each field.

2.2. Fields Surveyed

At the time of the initiation of this project the smallest localizations available had been obtained by timing GRB wavefronts on spacecraft scattered across the solar system by the First Interplanetary Network (IPN¹; Cline et al. 1980). The baseline criteria for inclusion in the survey were that the bursts (i) had high-quality localizations (≤ 70 arcmin²) and (ii) would be well-situated for observation from the Flagstaff Station of the US Naval Observatory (transit zenith angle of ≤ 60 deg). The localizations which met these criteria are listed in Table 1, along with the centers of the localizations, their Galactic coordinates, the sources of the localizations, and references to previous investigations of these fields. The latter include optical, infrared, and radio surveys, archival plate searches, spectroscopic surveys, and proper motion studies. Four of these fields were not surveyed, as explained below, but we leave them in Table 1 for information sake.

It was decided at the outset that observations would not be obtained for the localization of GBS 0116–28, due to the relatively large amount of work previously done on it, or for GBS 2311 + 32, since it had a relatively large error box and was in competition with other localizations at nearby hour angles. Some frames were obtained of the GBS 1925+04 field. However, due to the crowded nature of this field it was decided that photometry to a depth and accuracy commensurate with the rest of the survey would not be easily achieved and observations were terminated. A few frames were also obtained of the localization of GBS 1810 + 31, but it was soon realized that the nearby $V = 4.9$ star 104 Her would preclude a deep survey and observations of the IPN localization were terminated. However, at that time, we learned of a nearby archival OT event (OT 460831; Hudec 1988; Hudec, Peřesty, & Motch 1990) possibly associated with GBS 1810 + 31 and for the duration of the survey we obtained frames of this field. It was subsequently suggested (Hartmann et al. 1989) that this OT, which lies approximately 5 arcmin outside the current GBS 1810+31 error box, cannot be associated with the GRB event on the basis of proper motion limits. However, we include data for the objects in the OT field here as a supplement to the genuine GRB fields and to augment our discussions below of the statistics of galaxies and stars found in these fields. It should be noted that, although OT 460831 is not associated with a known GRB, its potential quiescent counterpart is of interest which we report on elsewhere (Vrba et al. 1995).

2.3. Instrumentation

All observations were obtained with the US Naval Observatory 1.0 m $f/7.2$ telescope located near Flagstaff, AZ. Two identical thinned, backside-illuminated TI 800² CCDs with 15 μ m pixels were employed during the 5 years of observations. Before each observing run the CCDs were UV-flooded in an O₂-soaked environment in order to enhance their UV sensitivity. Observations were obtained through the standard Johnson UBV and Kron-Cousins I passbands.

2.4. Field Registrations

The 22.18 arcsec mm⁻¹ focal plane scale of the 1.0 m telescope produces a field of approximately 5.7×5.7 with the TI

TABLE 1

GAMMA-RAY BURST LOCALIZATIONS MEETING SURVEY CRITERIA

GRB Event	Center $\alpha/\delta(1950)$	l^{II}/b^{II}	Local. Source	Previous Investigations					
				Optical	IR	Archival	μ	Spec	Radio
GB 791116/ GBS 0010-16	00 ^h 10 ^m 15.2 ^s -15°58' 46.3"	83° -76°	1		7				24
GB 781119/ GBS 0116-28	01 ^h 16 ^m 32.0 ^s -28°53'	228° -84°	2	9,10,12, 13,14	7	8,9	14	10	11,24
GB 790418/ GBS 0552-08	05 ^h 51 ^m 55.1 ^s -06°58' 51.0"	213° -16°	3	3,15	7	26			24
GB 790329/ GBS 1028+46	10 ^h 28 ^m 07 ^s +45°53' 45"	170° +57°	4	16	7	4,26	16		24
GB 781124/ GBS 1205+23	12 ^h 05 ^m 09.7 ^s +23°55' 49.4"	240° +77°	1	25	7	27	25		24
GB 790613/ GBS 1412+79	14 ^h 12 ^m 28.0 ^s +78°55' 18.7"	118° +38°	5	3,5,25	7	17,26	18,25		24
GB 790325b/ GBS 1810+31	18 ^h 09 ^m 53 ^s +31°23' 33"	58° +21°	4	4	7	4,26			24
OT 460831/ OTS 1809+31	18 ^h 09 ^m 27 ^s +31°23'	58° +21°	N/A	20,21		19	22		
GB 790331/ GBS 1925+04	19 ^h 25 ^m 30 ^s +03°34' 38"	41° -07°	4		7	4,26		23	24
GB 781104b/ GBS 2006-22	20 ^h 06 ^m -21°36'	21° -26°	3	3,15	7	28		3	24
GB 791105b/ GBS 2252-03	22 ^h 51 ^m 42.6 ^s -02°34' 26.0"	72° -50°	1		7	8,27		18	24
GB 790504/ GBS 2311+32	23 ^h 11 ^m 08.9 ^s +31°51' 19"	100° -26°	6		7	26			

REFERENCES.—(1) Cline et al. 1984; (2) Cline et al. 1981; (3) Hurley 1985; (4) Laros et al. 1985; (5) Barat et al. 1984; (6) Atteia et al. 1987; (7) Schaefer et al. 1987; (8) Schaefer et al. 1984; (9) Schaefer 1981; (10) Fishman et al. 1981; (11) Hjellming & Ewald 1981; (12) Schaefer & Ricker 1983; (13) Pedersen et al. 1983; (14) Schaefer et al. 1983; (15) Hurley 1982; (16) Harrison et al. 1994a; (17) Schaefer 1987; (18) Ricker et al. 1986; (19) Hudec et al. 1990; (20) Ricker et al. 1989; (21) Motch et al. 1990; (22) Hartmann et al. 1989; (23) Hartmann & Pogge 1987; (24) Schaefer et al. 1989; (25) Harrison et al. 1994b; (26) Hudec et al. 1987; (27) Greiner et al. 1978; (28) Hudec 1995.

800 CCD. This field size is large enough to cover the 99% confidence localizations in a single telescope pointing for GBS 0010-16, GBS 0552-08, GBS 1412+79, and OT 1809+31, while two registrations were required for GBS 1028+46, GBS 1205+23, and GBS 2006-22, and three registrations were required for GBS 2252-03. Figures 1a-1h display the final registrations for each of these fields along with 99% confidence GRB localizations referenced in Table 1. Table 2 lists the areas of the 99% confidence localizations, the actual areas surveyed by the adopted telescope registrations, their ratios, and the areas of the 99% confidence localizations that were not surveyed due to their large areas or long major axes. While there is a considerable range from field to field, the mean oversampling ratio of 2.2 for the 99% localizations and the fact that only about 9% of the localization areas were not surveyed make it highly likely that, absent large systematic localization errors, the actual GRB positions are within the areas covered by this study.

2.5. Observations Obtained

Between UT 1987 July 18 and UT 1992 30 the 1.0 m telescope was typically scheduled for 3 nights of dark to gray time each month for this project. Some of the nights were devoted to all-sky calibration photometry to set up local standards in

each field, as explained below. Such nights were otherwise sacrificed to other all-sky photometric programs, including support of the USNO parallax program. These short (typically 5 minutes) calibration exposures provided photometry for the brighter stars in each field. Normal program exposures were 60 minutes for the *BVI* filters and 100 minutes for the *U* filter. Such long exposures were possible since the thinned CCDs used are not subject to a high degree of cosmic-ray contamination. Most of the frames were obtained in the *V* and *I* bandpasses since, due to the red peak sensitivity of CCDs, we desired to get variability and proper motion data for as many objects as possible. The *U* and *B* filter data were aimed primarily at extending the wavelength baseline for color data and, hence, did not need to be as repetitive. Table 3 gives the number of frames and hours of open shutter time obtained for each field in each passband. A total of 273.6 hours of open shutter time was eventually obtained for the survey.

2.6. Data Reduction and Calibration

At the beginning of each night of observation flat-field frames were obtained of the twilight sky along with bias frames. At the end of each monthly observing run the program frames were flattened and debiased and archived on tape. Other than cursory inspection of the frames for obvious flash

FIG. 1.—(a) Field surveyed for the GBS 0010–16/GB 791116 event. The approximate 99% confidence localization is shown along with objects of potential interest discussed in § 8.1. The scale is shown at the bottom. North is in the direction of the field name, east is to the left of this.

events at the time of observation, no reductions were carried out for any field until after about 2 years of data were obtained. After this amount of time enough frames had been obtained such that a fiducial frame could reasonably be selected for each field. The fiducial frame was selected to be the frame with the greatest number of objects detected. In all cases this was an *I*-filter frame (due both to the red sensitivity of the CCD and the predominance of red stars) taken, up to that point in time, with a combination of best seeing and sky transparency. A pixel coordinate list was then generated for every object that was detected on the fiducial frame, even if it was obvious that the object was too faint for photometry on that frame. For every frame the fiducial coordinate list was reregistered, using a few well-exposed stars to account for small differences in telescope pointing, and overlaid on the frame. Each frame was

then inspected for new objects which might have been missed on the fiducial frame due either to variability or unusual colors. In fact, four additional objects were discovered in this fashion. However, they were all near the frame detection limits and it is not clear whether they are variable objects or simply detected on frames taken in better atmospheric conditions subsequent to the fiducial frame.

Photometry was obtained for all fiducial object positions on every frame in the survey using both aperture and profile-fitting routines in DAOPHOT (Stetson 1987). Profile-fit results were retained as the instrumental magnitudes of the database due to its superior performance, over that of aperture photometry, for crowded fields and faint stars. However, observations of objects with any of the following properties were excluded from the database; (1) images on known CCD chip

FIG. 1.—(b) Same as for Fig. 1a, but for the GBS 0552–08/GB 790184 event. The objects of potential interest are discussed in § 8.2.

defects, (2) images exceeding the CCD linearity range due to saturation, (3) images for which DAOPHOT exceeded 50 iterations in attempting to fit a profile, (4) images with DAOPHOT profile-fitting $\chi^2 > 5$, and (5) images with DAOPHOT photometric errors of $\sigma > 0.20$ mag. The last two of these criteria need some explanation. Images with profile-fitting χ^2 significantly larger than the normal 1.0 are of extended objects, assumed to be galaxies. While any extension beyond a normal stellar PSF degrades photometric accuracy, the errors introduced by a nonstellar PSF below $\chi^2 = 5$ for the purposes of this survey and in the context of photon statistics and transformation errors (described below) are insignificant. Photometry of bright galaxies with $\chi^2 > 5$ was recovered with aperture photometry. Finally, objects with DAOPHOT photometric errors of $\sigma > 0.20$ are faint. Our experience has shown

that despite DAOPHOT's best efforts to account properly for such components as sky levels the magnitudes and σ 's themselves are unreliable beyond $\sigma > 0.20$.

At this point the 302 original CCD frames had been converted into 302 lists of uncalibrated instrumental magnitudes. Conversion of the instrumental *BVI* magnitudes to standard system photometry was accomplished by setting up a system of 10 to 20 local standards in each field in the magnitude range $16 < V < 22$. Short exposures (5–10 minutes) were obtained of each field in *BVI* on at least two different nights when all sky photometry was being obtained in support of the USNO parallax program. Reductions of the preselected local standards to the standard system defined by Landolt (1992) were kindly carried out by H. Harris. Errors of the local standard photometry ranged from 0.01 mag for the brightest stars to

FIG. 1.—(c) Same as for Fig. 1a, but for the GBS 1028 + 46/GB 790329 event. The objects of potential interest are discussed in § 8.3.

FIG. 1.—(d) Same as for Fig. 1a, but for the GBS 1205 + 23/GB 781124 event. The objects of potential interest are discussed in § 8.4.

FIG. 1.—(e) Same as for Fig. 1a, but for the GBS 1412 + 79/GB 790136 event. The objects of potential interest are discussed in § 8.5.

0.10 mag for the faintest. Having local standards in each field greatly increased the efficiency of the survey since it (1) obviated the necessity for obtaining standard star calibration photometry each night, (2) greatly reduced the data reduction tasks, and, most importantly, (3) allowed observations to be obtained through thin clouds on nights that otherwise would have been useless.

Conversion of the instrumental to standard magnitudes was done by a simple magnitude zero point calculated for each frame from the mean difference between standard and instrumental magnitudes for the local standards. The mean zero point for each frame was calculated by weighting the magnitude difference for each standard star by

$$1/\sigma_{s+i}^2 = 1/[(\sigma_s)^2 + (\sigma_i)^2], \quad (1)$$

where σ_s and σ_i are the uncertainties of the standard and instrumental values, respectively. This technique ignores any color terms which might exist in the CCD/filter system we used. While this may be disquieting to photometrists, we chose this path for three simple reasons. First, our extensive experience with this CCD/filter system in doing high-accuracy photometry led us to understand that uncorrected color terms would be minimal. Second, the nature of this survey is to look for objects with outstanding color or variability properties; hence, a small increase in systematic color and magnitude errors would be inconsequential. Finally, this allowed an additional degree of freedom in observing, in that matched pairs of long exposures would not have to be obtained in order to provide a color basis. Figures 2a–2c plot the true (standard) versus observed values for all of the local standard stars for V ,

FIG. 1.—(f) Same as for Fig. 1a, but for the OTS 1809 + 31/OT 460831 event. There is no GRB localization shown since, as explained in § 2.2, this OT is thought not to be associated with a GRB event. The objects of potential interest are discussed in § 8.6.

$(V-I)$, and $(B-V)$, respectively. The solid lines are the slope = 1.00 lines. The actual slopes and rms scatter about the lines are:

$$V_{\text{Obs}} = 1.000(V)_{\text{True}}, \quad \sigma = 0.041 \text{ mag}; \quad (2)$$

$$(V-I)_{\text{Obs}} = 0.996(V-I)_{\text{True}}, \quad \sigma = 0.033 \text{ mag}; \quad (3)$$

$$(B-V)_{\text{Obs}} = 0.992(B-V)_{\text{True}}, \quad \sigma = 0.036 \text{ mag}. \quad (4)$$

Thus, there appear to be no significant color or magnitude effects over the color range of the standard stars. The reason that the rms scatter is as large as it is, is that fainter stars are well-exposed on a typical program frame, but weakly exposed on the calibration frames, while brighter stars are well-exposed on the calibration frames, but nearing or slightly saturated on

a typical program frame. For a typical frame having 10 local standards, the error introduced by applying the calibration is $(\text{rms})/10^{1/2} \approx 0.01 \text{ mag}$.

Unfortunately, all-sky calibration photometry was not obtained for the U filter, as U observations are not typically obtained in support of the USNO parallax program. In order to roughly calibrate the U observations, we assigned a $U-B$ color, and hence U magnitude, to each local standard on the basis of its $B-V$ and $V-I$ colors and under the assumption that it is a main-sequence star with no reddening. The former assumption is reasonable, since most stars encountered will be main-sequence; however, the second assumption almost certainly is not. Fortunately, for the color range of the local standards, the $(U-B)$, $(B-V)$, $(V-I)$ vectors for normal

FIG. 1.—(g) Same as for Fig. 1a, but for the GBS 2006–22/GB 781104b event. The objects of potential interest are discussed in § 8.7.

FIG. 1.—(h) Same as for Fig. 1a, but for the GBS 2252—03/GB 791105b event. In addition, the approximate position of the Schaefer et al. (1984) UT 1901 October 04 (OT 011004), discussed in § 8.8, is shown by the small ellipse. The objects of potential interest are discussed in § 8.8.

TABLE 2

GAMMA-RAY BURST LOCALIZATIONS SURVEYED

GRB Event	99% Confidence Localization Area arcmin ²	Area Surveyed arcmin ²	Oversampling Ratio	99% Confidence Area Missed arcmin ²
GB 791116/ GBS 0010-16	4.5	32.5	7.2	0.0
GB 790418/ GBS 0552-08	2.9	32.5	11.2	0.0
GB 790329/ GBS 1028+46	41	62.0	1.5	1
GB 781124/ GBS 1205+23	62	63.1	1.0	6
GB 790613/ GBS 1412+79	0.7	32.5	46.4	<0.04
OT 460831/ [†] OTS 1809+31	NA [†]	32.5 [†]	— [†]	— [†]
GB 781104b/ GBS 2006-22	14	54.2	3.9	0
GB 791105b/ GBS 2252-03	41	81.9	2.0	8
TOTALS	166	359	2.2	15

[†] Not included in totals.

interstellar reddening are nearly parallel to the main-sequence locus. Thus, the nearly correct $(U-B)$ color will be derived from the $(B-V)$, $(V-I)$ colors, albeit for the wrong reason. To test the validity of this technique we have plotted in Figure 2d the inferred $(U-B)$ colors of the local standards versus their calibrated $(B-V)$ colors along with a solid line representing

TABLE 3

SUMMARY OF OBSERVATIONS

GRB Field	Number frames (Number hours)				
	U	B	V	I	Σ
GB 791116/ GBS 0010-16	2(3.4)	6(5.3)	12(9.0)	10(6.8)	30(24.5)
GB 790418/ GBS 0552-08	2(3.4)	5(4.3)	17(13.8)	13(10.3)	37(31.8)
GB 790329/ GBS 1028+46	4(6.7)	9(8.4)	21(17.8)	12(9.3)	46(42.2)
GB 781124/ GBS 1205+23	4(6.7)	10(9.0)	16(12.3)	10(7.0)	40(35.0)
GB 790613/ GBS 1412+79	2(3.3)	6(5.2)	16(13.2)	12(9.7)	36(31.4)
OT 460831/ OTS 1809+31	2(3.3)	6(5.1)	26(24.2)	14(11.4)	48(44.0)
GB 781104b/ GBS 2006-22	4(6.7)	5(4.2)	9(6.7)	7(5.3)	25(22.9)
GB 791105b/ GBS 2252-03	6(10.0)	9(6.8)	17(15.2)	12(9.8)	44(41.8)
TOTALS	25(43.0)	53(48.3)	134(112.2)	90(69.6)	302(273.6)

the main-sequence. The data points follow the main-sequence locus closely but with a scatter of $(\text{rms}) \approx 0.10$ mag. For a typical frame having 10 local standards, the error introduced by applying the calibration is $(\text{rms})/10^{1/2} \approx 0.03$ mag. This appears to be wholly adequate for the purpose of finding objects with highly unusual colors.

The final magnitudes for each observation were then obtained by applying the calibrations determined above for each frame and calculating the final error of the observation by

$$\sigma_{\text{phot}} = [\sigma_{\text{DAO}}^2 + \sigma_{\text{calib}}^2]^{1/2}, \quad (5)$$

where σ_{DAO} is the internal error of the observation determined by DAOPHOT and σ_{calib} is the standard deviation of the mean calibration offset weighted by σ_{s+i}^{-2} , as described above.

2.7. The Database

The fundamental database consists of 302 tables of calibrated U , B , V , or I photometry totaling more than 79,000 observations of 2070 objects. While it is tempting to merely present our analysis of these data, we feel that the database should be available for external analysis. Clearly, it is unreasonable to print publish the database. Additionally, the publication, in any medium, of the entire data base probably would be useful to only a limited number of people and would likely require private discussion in order for the database to be fully exploited. Accordingly, we have decided to publish in the AAS CD-ROM Series, Vol. 5, a compacted version of the database, a sample of which is presented in Table 4. The fields are listed in order of increasing Galactic latitude. In column (1) the object identification numbers are given, which are in order of decreasing declination. The four objects with numbers 901+ are those found on frames other than the fiducial frames, as described in § 2.6. Columns (2)–(11) give V , $B-V$, $U-B$, $V-I$, $U-V$, and their respective uncertainties for each object using all of the data in the survey passing the criteria listed in § 2.6. The colors and magnitudes are mean values calculated by weighting each datum point by $\sigma_{\text{phot}}^{-2}$. The uncertainties listed for the V filter, $\sigma(V)$ are the larger of (1) the weighted standard deviation of the mean or (2) the minimum error

$$\left[\sum_{i=1}^n (\sigma_{\text{phot}})^{-2} \right]^{-1/2}. \quad (6)$$

Thus the listed error represents the uncertainty of the value whether primarily due to photometric error or variability. The uncertainties for the colors are calculated from

$$\sigma(U-B) = [\sigma(U)^2 + \sigma(B)^2]^{1/2}; \quad (7)$$

$$\sigma(B-V) = [\sigma(B)^2 + \sigma(V)^2]^{1/2}; \quad (8)$$

$$\sigma(V-I) = [\sigma(V)^2 + \sigma(I)^2]^{1/2}; \quad (9)$$

$$\sigma(U-V) = [\sigma(U)^2 + \sigma(V)^2]^{1/2}. \quad (10)$$

A -9.000 or -1.000 in the color/magnitude and uncertainty columns, respectively, indicates that there are insufficient data to calculate that quantity. In columns (12) and (13) we list the fiducial pixel coordinates of each object to the nearest 0.1 pixel, although the centroids of the faintest objects and extended objects are known to only $\approx \pm 1.0$ pixel. Additionally, the CCD orientation is known to only ± 0.5 deg, thus X , Y do not correspond directly to α , δ . For objects which lie as far as 400 pixels from the center of the field, this can correspond to an

FIG. 2.—Panels (a)–(c) plot the observed V , $(V-I)$, and $(B-V)$ magnitudes and colors, respectively, determined in this survey vs. formally determined magnitudes and colors, V_{True} , $(V-I)_{\text{True}}$, and $(B-V)_{\text{True}}$ for 10–20 local standard stars in each field. The straight lines are not fits to the data, but slope = 1.00 lines, for reference. Panel (d) plots the inferred $(U-B)$ colors of the local standards versus their calibrated $(B-V)$ colors, along with a solid curve showing the main-sequence. None of these panels indicates that significant systematic differences from standard colors occur for photometric data in this survey.

additional error of

$$400 \tan(0.5 \text{ deg}) \approx 3.5 \text{ pixels}.$$

At the telescope pixelization of $0.4295 \text{ arcsec pixel}^{-1}$ the combined errors could be as large as $\approx 2 \text{ arcsec}$. Thus, the pixel coordinates should be used for identification purposes only and not for high accuracy astrometry.

2.8. Limiting Magnitudes

A graphical depiction of the actual limiting magnitudes of the survey is given in Figure 3. For the U , B , V , and I filters, magnitudes are shown for 5% photometry, 20% photometry, and the detection limits. These are the averaged magnitudes for the single best seeing/sky transparency frame for each field at which $\sigma_{\text{phot}} = 0.05 \text{ mag}$, $\sigma_{\text{phot}} = 0.20 \text{ mag}$, and at which objects are clearly detected above the sky background, respectively. In addition, for the V filter we show the average magnitude at which the faintest galaxies are spatially resolved. The error bars shown represent the standard deviations of these values for the eight fields. The relatively large ranges of these values are due to the fact that the transit zenith angle for the eight

fields ranged from 4 to 58 degrees. Fields with large values of transit zenith angles suffered worse seeing and higher atmospheric extinction than those typically observed at lower air mass.

3. OBSERVATIONS OF THE KNOWN UNIVERSE

Before we can discuss what objects the database has revealed to be extraordinary in any regard, it is important to understand whether or not the survey successfully detected that which is expected. In the next two sections we compare, as a test of our database, the numbers of detected galaxies and stars with those predicted from extragalactic and Galactic structure surveys, to the relevant limiting magnitudes.

3.1. Galaxy Populations

As Figure 3 shows, the mean limiting magnitude for the detection of resolved galaxies in the survey is $V = 21.6$, with considerable scatter due to declination effects. Detection of resolved or partially resolved galaxies above this magnitude limit was accomplished by visual inspection of the best-seeing frames and analysis of the “sharpness” parameter provided by

TABLE 4
SAMPLE OF CONDENSED DATABASE

Object	V	$\sigma(V)$	B-V	$\sigma(B-V)$	U-B	$\sigma(U-B)$	V-I	$\sigma(V-I)$	U-V	$\sigma(U-V)$	X(pix)	Y(pix)
GBS 0552-08												
1	16.515	0.009	0.753	0.017	0.360	0.050	0.971	0.012	1.113	0.049	659.3	6.5
2	18.355	0.008	0.958	0.022	0.707	0.055	1.140	0.009	1.665	0.052	209.9	8.8
3	20.986	0.023	1.639	0.078	-9.000	-1.000	2.044	0.027	-9.000	-1.000	66.3	16.1
4	17.978	0.006	0.705	0.019	0.336	0.051	0.942	0.010	1.041	0.048	160.4	19.1
5	21.048	0.023	1.330	0.065	-9.000	-1.000	1.568	0.044	-9.000	-1.000	36.9	23.5
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
283	20.373	0.044	1.595	0.066	-9.000	-1.000	1.971	0.047	-9.000	-1.000	662.0	800.0
OTS 1810+31												
1	22.433	0.052	-9.000	-1.000	-9.000	-1.000	2.412	0.063	-9.000	-1.000	22.0	3.0
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
373	17.189	0.006	0.970	0.010	0.803	0.032	1.088	0.009	1.773	0.032	364.9	793.5
GBS 2006-22												
1	18.073	0.017	1.260	0.025	1.261	0.074	1.446	0.018	2.521	0.074	41.6	12.1
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
431	19.700	0.020	0.641	0.030	0.263	0.102	0.742	0.080	0.904	0.101	179.5	1355.8
GBS 1412+79												
1	22.306	0.083	1.183	0.186	-9.000	-1.000	1.814	0.125	-9.000	-1.000	489.0	2.0
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
132	20.678	0.020	0.695	0.050	-9.000	-1.000	0.700	0.075	-9.000	-1.000	600.0	792.0
GBS 2252-03												
1	19.375	0.022	1.111	0.035	0.984	0.151	1.271	0.034	2.095	0.150	449.9	12.9
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
274	18.952	0.020	-9.000	-1.000	-9.000	-1.000	0.752	0.024	-9.000	-1.000	14.9	1749.4
GBS 1028+46												
1	22.837	0.114	0.769	0.227	-9.000	-1.000	2.531	0.146	-9.000	-1.000	1286.2	5.5
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
902	21.931	0.136	0.567	0.166	-9.000	-1.000	0.864	0.189	-9.000	-1.000	1073.6	180.6
GBS 0010-16												
1	-9.000	-1.000	-9.000	-1.000	-9.000	-1.000	-9.000	-1.000	-9.000	-1.000	557.0	5.0
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
902	21.185	0.053	-9.000	-1.000	-9.000	-1.000	-9.000	-1.000	-9.000	-1.000	438.1	797.1
GBS 1205+23												
1	21.969	0.143	-9.000	-1.000	-9.000	-1.000	1.502	0.174	-9.000	-1.000	323.0	11.0
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
267	19.619	0.009	1.401	0.051	-9.000	-1.000	2.350	0.024	-9.000	-1.000	1025.5	1498.7

NOTE.—Table 4 is presented in its complete form in the AAS CD-ROM Series, Vol. 5, 1995. The first five lines and subsequent layout are presented here for guidance regarding its form and content.

FIG. 3.—Mean limiting magnitudes for the U, B, V, and I bandpasses, based on the best-seeing frames for each field are shown for the 5%, 20%, and detection photometric levels. In addition, the resolution limiting magnitude is shown for the V filter. The error bars show the standard deviations for the eight fields, which are primarily due to the large range in zenith distances for the fields.

the profile fitting routine in DAOPHOT. Column (2) of Table 5 lists the number of resolved galaxies found for each field, with a total for the survey of 123. The logarithm of the number of resolved galaxies normalized per square degree for each field is plotted versus the absolute value of the Galactic latitude $|b^{\text{II}}|$ in Figure 4. The error bars are from $n^{1/2}$ statistics of the galaxy counts. The curves represent the Tyson & Jarvis (1979) galaxy count relation,

$$\log N = 0.41J - 5.63(\text{galaxies deg}^{-2}), \quad 17 \leq J \leq 24 \text{ mag}, \quad (11)$$

which has been modified to account for the wide range of Galactic reddening relations represented in the literature. The nominal $V = 21.6$ galaxy detection magnitude limit was decreased by the differential Galactic extinction to give an effective galaxy detection limit as a function of $|b^{\text{II}}|$. The minimum extinction we used, $A_V = 0.15 \text{ csc}(|b^{\text{II}}|)$ (de Vaucouleurs, de Vaucouleurs, & Corwin 1976), and the maximum extinction we used, $A_V = 0.39 \text{ csc}(|b^{\text{II}}|)$ (Mihalas & Binney 1981), give, respectively,

$$\log N = 0.41[V - 0.15 \text{ csc}(|b^{\text{II}}|) - 1] - 5.63, \quad (12)$$

$$\log N = 0.41[V - 0.39 \text{ csc}(|b^{\text{II}}|) - 1] - 5.63. \quad (13)$$

In this formulation we assume that the “green” J filter approximates the standard V filter. Inspection of Figure 4 shows that

TABLE 5
GALAXIES WITHIN FIELDS SURVEYED

GRB Event	Galaxies			$N_{\text{GAL}} = N_R + 2(N_A) + N_B$	$N_{\text{GAL}}/N_{\text{OBJECTS}}$ (%)
	N_R	N_A	N_B		
GB 790418/ GBS 0552-08	2	12	0	26	9%
OT 460831 OTS 1809+31	6	28	2	64	17%
GB 781104b/ GBS 2006-22	4	17	4	42	10%
GB 790613/ GBS 1412+79	14	19	3	55	42%
GB 791105b/ GBS 2252-03	21	43	4	111	41%
GB 790329/ GBS 1028+46	31	49	6	135	65%
GB 791116/ GBS 0010-16	13	20	4	57	55%
GB 781124/ GBS 1205+23	32	55	18	160	60%
TOTALS	123	243	41	650	31%

we detected approximately the expected numbers of resolved galaxies for $|b^{\text{II}}| \geq 30^\circ$. At lower $|b^{\text{II}}|$ there is a clear decrease in the number density of galaxies detected which, if anything, is more consistent with the higher Galactic extinction relation, although the numbers of galaxies detected is small and, hence, the uncertainties large. The only data point which falls significantly below the curves is at $|b^{\text{II}}| = 26$, which is of the low declination, high air mass field GRB 2006-22.

Since the resolved galaxies are detected only at the brighter end of the survey, there clearly must be many other unresolved galaxies at fainter magnitudes which we can only attempt to distinguish by photometry. Figure 5 illustrates the difficulty in separating stars from galaxies in the $(B - V)$ versus $(V - I)$ two-

FIG. 4.—Logarithm of the number of galaxies per square degree is plotted versus the absolute value of Galactic latitude for each field. The curves represent the galaxy counts of Tyson & Jarvis (1979) with different values of Galactic extinction.

color diagram. The solid polygon represents the approximate uniformly filled locus of colors for resolved galaxies in this survey (discussed in detail in § 6). The long solid curve represents the main-sequence, while the dashed curves represent the approximate width of the main-sequence locus from photometry in this survey (discussed in detail in § 5). Galaxies lie generally to the left of the main-sequence line, due to their having spectral energy distributions typically broader than for single stars, but with the uniformly filled locus of resolved galaxies having an approximately 50% overlap in area with the stellar main-sequence locus. A few galaxies will lie still further to the left of the uniformly filled galaxy locus. Removing the resolved galaxy photometry from this plot, we can then estimate the total number of galaxies in each field from

$$N_{\text{GAL}} = 2(N_A) + N_B + N_R, \tag{14}$$

where N_A is the number of objects lying in the region of the uniformly filled galaxy locus not affected by main-sequence stars (region A in Fig. 5), N_B is the number of objects lying further to the left of region A, and N_R is the previously determined number of resolved galaxies. These statistics are compiled in Table 5 for each field and for the total survey, where the fields are listed in increasing order of absolute value of Galactic latitude $|b^{\text{II}}|$. In the last column of Table 5 we list the ratio of N_{GAL} to the total number of objects detected in each field, which clearly increases toward higher Galactic latitudes. However, we caution that the numbers listed in this column are lower limits to the actual galaxy/object ratio, since many detected objects may be galaxies but too faint to have photometry meeting the quality criteria of § 2.6.

In Figure 6 we plot the logarithm of N_{GAL} , which has been normalized per square degree, with respect to that predicted by Tyson & Jarvis (1979) for each of the fields. The predicted $\log(N)$ comes from the same formulation given above for Galactic extinction of $A_V = 0.39 \text{ csc}(|b^{\text{II}}|)$, except that the

FIG. 5.—Schematic showing the location of galaxies in the $(B - V)$, $(V - I)$ diagram. The polygon represents the approximate region which is uniformly filled by resolved galaxies in this survey. The solid and dashed curves represent the location and width of the main sequence, respectively. The separation of galaxies into regions A and B is discussed in § 3.1.

FIG. 6.—Plot of the logarithm of the total number of resolved and photometrically detected galaxies per square degree detected in each region vs. that predicted from the galaxy counts of Tyson & Jarvis (1979).

mean $V = 21.6$ resolved galaxy detection limit is now replaced by the 20% photometry limit for each field, since availability of photometric colors now limits the galaxy statistics. The 20% photometry limit is in the range $22.0 \leq V \leq 22.9$, depending on the field. The straight line in Figure 6 is not a fit to the data, but the slope = 1.0 line for reference. The error bars for the observations are derived from $n^{1/2}$ statistics of the galaxy counts. While there is considerable scatter in the data, it is clear that this survey has detected approximately the number density of galaxies for both the resolution—and photometry—limited cases as predicted by the Tyson & Jarvis (1979) data.

3.2. Stellar Populations

Now that we have estimates of the galaxy counts for each field, we turn our attention to star counts in the fields. In Figures 7a–7h we plot histograms, for each field, of the integrated number of objects per magnitude interval in the V filter, normalized per square degree. In Figures 8a–8h we do the same for the B filter. In both figures the fields are shown in order of increasing values of $|b^{\text{II}}|$. Also, in both cases we have removed the spatially resolved galaxies from the data sets. We have not removed the photometrically determined galaxies from the data sets since, from the discussion above, only about 50% of these can be clearly identified. The curves shown are the predicted stellar densities from the Galactic structure models of Bahcall & Soneira (1980, hereafter B&S) at the Galactic ($l^{\text{II}}, b^{\text{II}}$) of each field. The curves were calculated using the approximation equation (B1) and coefficients (B2) of B&S, which are quoted as having a typical average absolute error of 15%. The upper and lower curves are calculated using the minimum and maximum Galactic extinction relations of § 3.1, respectively, $A_V = 0.15 \text{ csc}(|b^{\text{II}}|)$ and $A_V = 0.39 \text{ csc}(|b^{\text{II}}|)$.

There are a number of points to be made from these figures. First, for all fields the B&S models are consistent with the object density to approximately $V, B \leq 21.5$. Recall that this is the approximate magnitude level to which we were able to identify resolved galaxies in the previous section, and that we have removed such galaxies from these histograms. For the

three fields at the lowest Galactic latitudes ($|b^{\text{II}}| \leq 26$ degrees), the B&S models are consistent with the models to the limit of the photometry. We note that the object number density for GBS 2006–22 is somewhat lower than the models predict. This is due to the fact that this field has the shallowest photometry due to its being at the largest airmass and having fewest CCD frames due to competition by fields at surrounding right ascensions.

For fields at higher Galactic latitudes ($|b^{\text{II}}| \geq 38$ degrees), however, there are clearly many more faint objects than the models predict. While it seems apparent that these additional objects must be unresolved faint galaxies not accounted for by the model stellar distribution, it is also possible that either (1) the model is faulty, and/or (2) there is some unaccounted low light level sensitivity bias in the survey data. While these latter possibilities seem unlikely, we can nevertheless make the following test. Since both the object histograms and the photometric galaxy count of the previous section are limited at the same magnitude level per field, those unresolved galaxies should be the same population responsible for the excess objects in the histograms. From Table 5 we find the number of unresolved galaxies to be $2(N_A) + N_B = 527$. For the histograms, we take the integrated object count in excess of the mean of the two B&S curves and convert this back to object count per surveyed area. In the V filter we obtain a total of 534 excess objects, and in the B filter we obtain 335 excess objects. These counts are consistent with the earlier unresolved galaxy estimates, considering the uncertainties of all of the methods employed. We also note that both this count comparison and the B&S curves for the low Galactic latitude fields provide some mild support for a smaller, rather than larger, value of Galactic extinction.

4. COLOR-COLOR DIAGRAMS

In this section we describe the results of the main color-color diagrams which can be formed from the $UBVI$ photometry. Although individual objects of potential interest are marked in the color-color plots, we will defer discussing them until § 8, where we combine all of the data available to detect objects of interest.

In Figure 9a–9h we show the $(B-V)$ versus $(V-I)$ color-color plots for all eight fields in order of increasing value of $|b^{\text{II}}|$. As in the previous section all resolved galaxies have been removed from the data sets, as these will be discussed separately in § 6. The data plotted are the mean $(B-V)$ and $(V-I)$ colors and their uncertainties discussed in § 2.7. For each data set we also plot the position of the main-sequence as the solid curve. For reference, in the panel for the lightly populated GBS 1412+79 field, we also plot a curve for the locus of giant stars. In these plots one immediately notices the concentrations of objects to the left of the stellar loci, especially at higher $|b^{\text{II}}|$, which are the presumed unresolved galaxies discussed in the previous section. This color-color combination was chosen to reveal these galaxies since it goes deeper than other available color-color diagrams due to the sensitivity function of the CCD and to Galactic extinction.

In Figure 10a–10h we show the $(U-B)$ versus $(B-V)$ color-color plots for all eight fields in order of increasing value of $|b^{\text{II}}|$. As for the previous figure, all resolved galaxies have been removed from the data sets and the plotted error bars are derived in the same manner. Again the main-sequence locus is shown for all panels and also the giant locus is shown for

FIG. 7.—In panels (a)–(h) we plot histograms of the integrated number of objects per square per magnitude interval detected in this survey for each field respectively in the V filter. Resolved galaxies but not photometrically detected galaxies, as explained in § 3.2, have been removed from these counts. The solid curves represent the Galactic structure models of Bahcall & Soneira (1980) for two different values of Galactic reddening.

FIG. 8.—Same as for Fig. 7, except for the B filter

FIG. 9.—In panels (a)–(h) we show the $(B-V)$ vs. $(V-I)$ color-color diagrams for each field in order of increasing values of absolute Galactic latitude. Resolved galaxies have been removed from the data sets. The main-sequence locus is shown in each and, for reference, the giant star locus is also shown in the lightly populated panel (d). Objects of potential interest, discussed in § 8, are numbered if space is available in the panel.

FIG. 10.—Same as Fig. 10 except that the $(U-B)$ vs. $(V-I)$ color-color diagrams. Additionally, the solid polygon in panel (d) is the locus of white dwarfs (Eggen & Greenstein 1965, 1967), while the dashed polygon is the locus of QSOs from Basu (1986). The vertical dashed line is described in § 4.

FIG. 11.—Same as Fig. 10 except that the $(U-V)$ vs. $(V-I)$ color-color diagrams are shown. Additionally, the rectangle in panel (d) is the approximate locus of QSOs from Harris et al. 1992; Harris 1994).

FIG. 12.—For the GBS 0010–16 field, we plot the weighted standard deviations of the mean magnitudes as a function of brightness for the I , V , and B data, respectively, in panels (a)–(c) for objects with two or more observations. In panels (d)–(f) we plot the corresponding reduced χ^2 ($\chi^2/n - 1$) values for the I , V , and B data, respectively. Data for resolved galaxies have been removed from these data sets.

reference for the GBS 1412+79 panel. This color-color plot is sensitive to objects which show a UV excess over that expected from normal stars and to objects which do not display the normal-star Balmer decrement. Accordingly, in the GBS 1412+79 panel we have also plotted two other loci. The small polygon at the lower left of the figure bounded by the solid lines is the loci for white dwarfs (Eggen & Greenstein 1965, 1967). The larger polygon bounded by the dashed lines is the locus of QSOs from Basu (1986). This polygon is itself split by

the vertical line at $(U-B) \approx -0.35$. To the left of this line are where the majority of normal QSOs lie with $z \leq 1.0$. To the right of this line are an admixture of high z QSOs and weaker AGNs gradually merging with normal galaxies.

In Figures 11a–11h we show the $(U-V)$ versus $(V-I)$ color-color plots for all eight fields in a manner similar to the previous two figures. Again the main-sequence locus is shown for all panels and also the giant locus is shown for reference for the GBS 1412+79 panel. This color-color plot has the longest

FIG. 13.—Same as Fig. 12, except for the GBS 0552–08 field

wavelength baseline available from our data set and is particularly adept at identifying QSOs. This is because QSOs tend to have an especially flat spectral energy distribution in this wavelength region with respect even to normal galaxies. The rectangle shown in Figure 11*d* represents the approximate locus of QSOs in this diagram (Harris et al. 1992; Harris 1994). It is expected that weaker emission objects and those at high z will fall to the right and upper right of the rectangle, respectively. However, we caution that unresolved hot/cool stellar binaries can also mimic the position of QSOs in this diagram.

5. VARIABILITY

We now turn our attention to the question of variable sources which may have been detected in the survey. Variability-related plots are displayed for each field in Figures 12–19, respectively. As for previous analyses, the data for the resolved galaxies have been removed from these figures and will be discussed separately in the next section. Again, individual objects, although identified, will be discussed in § 8. In panels (a)–(c) we plot the weighted standard deviations of the

FIG. 14.—Same as Fig. 12, except for the GBS 1028+46 field

mean magnitudes for the I , V , and B , filters, respectively, against the mean magnitude for each object with two or more observations. The plots of $\sigma(I, V, B)$ are intended to show the envelope of photometric uncertainty as a function of magnitude, outside of which an object may be suspected of being unusually variable. Clearly, the envelope may be expanded somewhat by the inclusion of common stars with small degrees of variability. However, our interests are in the discovery of objects with variability amplitudes well above such levels. In panels (d)–(f) we plot the reduced χ^2 [$\chi^2/(n-1)$] for each

object with two or more observations. χ^2 , normalized by the number of degrees of freedom, allows χ^2 to be directly comparable for objects with different numbers of observations. We remind the reader that objects in this survey typically have differing numbers of observations due to differences in frame exposure times, seeing variations, and slight changes in frame registration. The reduced χ^2 plots show which objects have a large standard deviation of the mean with respect to that predicted by the uncertainties of the individual observations (eq. [6]). Since only a few frames of each field were obtained with

FIG. 15.—Same as Fig. 12, except for the GBS 1205+23 field

the U filter, those frames were not considered for variability analysis.

Several comments are needed regarding these figures. First, some of the stars at the bright end of the magnitude range show some apparent, but false, evidence for variability. It was our decision to extend the magnitude range of the data sets as far to the bright end as possible, since it would be particularly frustrating not to have data on the brighter objects in the field. While those images which were clearly saturated were deleted from the data sets, we did retain images with profile-fitting χ^2 's

as large as 5.0. In practice, this increases the photometric errors only slightly and still allows for the detection of objects with unusual colors or large variability at the expense of elevated values of photometric reduced χ^2 .

Second, it is apparent from Figures 12–19, panels (d)–(f) that we somewhat underestimated σ_{phot} for individual observations as the reduced χ^2 should average around 1.0 for non-variable stars. Much of this, no doubt, stems from the difficulty in quantitatively assessing the influence of long spatial wavelength errors in flat fielding. However, for identifying variable

FIG. 16.—Same as Fig. 12, except for the GBS 1412 + 79 field

objects, we are less interested in the absolute degree of variability than in finding objects which stand out from the envelope of normal objects. Additionally, we chose at the beginning of the project not to spend the extra overhead in observing time in obtaining the necessary calibration observations to get the non-photon-limited observational errors to the 1% level. Instead, we aimed for the 2%–3% accuracy level since we felt that identification of variability below the 5% level would be of little value, given that many otherwise normal stars are variable at this level.

Third, a comment on identifying variability. Typically, due to the long exposure times involved, only one or two observations were obtained of a particular field on a given night, so that the *BVI* data sets are largely uncorrelated in time. Thus, variability can be found by isolated light fluctuations on individual frames or by a continuing pattern of variability, but verification of variations on a given night by multiple frames of the field is not available typically. Thus, in preliminary analyses of the database every observation of every object which showed apparent evidence of variability was examined

FIG. 17.—Same as Fig. 12, except for the OTS 1809 + 31 field

for evidence of frame defects. This included examination of the χ^2 -values of the image fit to the mean point-spread function used for the frame, an image sharpness estimator, and visual inspection of the image itself. In fact, a number of individual observations were discarded from the database due to this. Typically, the observations were affected by a bad pixel, bad CCD column, cosmic-ray hit, or frame edge effects. Thus, the remaining evidence for variability, even if based on a single data point, should be fairly robust.

Finally, we wish to re-emphasize a point made in § 2.6. After

the fiducial coordinate system was established, it was overlaid on every frame taken of every field to search for new objects which either were quiescently below the survey limit and flared or which had a highly unusual color, since the deepest I frames were used to establish the fiducial coordinate system. There were in fact a few objects discovered in this fashion very near the frame limits. However, we can state that we found no clear evidence for an object bursting well above the detection threshold. Thus, depending upon the reader's choice of model burst amplitude and timescale for repetition, the survey is effectively

FIG. 18.—Same as Fig. 12, except for the GBS 2006–22 field

deeper than the stated detection limits for GRB sources quiescently below the survey magnitude limits, but caught in the act of optical brightening.

6. RESOLVED GALAXIES

We have chosen to discuss resolved galaxies separately for two reasons. First, because they are a clearly identified class of object on a basis independent of our photometric results. Secondly, the data reduction procedures were somewhat different and less reliable than for those for point source objects. The six

most extended galaxies were so large that we obtained photometry via synthetic apertures rather than via profile-fitting. The remaining galaxies, although partially resolved, were small enough to be comparable in size to the typical point spread function diameter used. For these objects we simply retained the profile-fit magnitudes. Under poor seeing conditions the photometry will be more reliable than under good seeing conditions and the σ_{DAO} portion of σ_{phot} will typically be underestimated, thus not providing the formally proper weighting to mean values. The net results are magnitudes and colors which

FIG. 19.—Same as Fig. 12, except for the GBS 2252–03 field

are suitable for placing objects in the color-color diagrams, but whose formal errors underestimate the true uncertainties by as much as 0.10 mag, depending on the size of the galaxy. The latter makes detection of variability difficult except for events with amplitudes significantly larger than 0.10 mag. Fortunately, we do not expect variability in normal nearby galaxies except for extraordinary events such as supernovae or for putative OT events.

In Figures 20a–20c we present, respectively, the $(B-V)$ versus $(V-I)$, $(U-B)$ versus $(B-V)$, and $(U-V)$ versus $(V-I)$

diagrams, for the combined resolved galaxies detected in all of the fields. As in earlier color-color plots we have superposed the main-sequence and giant branch loci for reference. One object is clearly identified as having a large UV excess and will be discussed in § 8.

In Figures 21a–21c we plot the photometric standard deviations of the means, $\sigma(I)$, $\sigma(V)$, and $\sigma(B)$, respectively, against the mean magnitude for all resolved galaxies with two or more observations. In panels (d)–(f) we plot the reduced χ^2 for all resolved galaxies with two or more observations. From the

FIG. 20.—In panels (a)–(c) we plot, respectively, the $(B-V)$ vs. $(V-I)$, $(U-B)$ vs. $(B-V)$, and $(U-V)$ vs. $(V-I)$ color-color plots for all resolved galaxies in this survey. The main-sequence and giant branch loci are shown in each panel. The locations are shown of interesting galaxies discussed in § 8.

caveats discussed above, $\sigma(B, V, I)$ is probably a better determinant of variability than $\chi^2/(n-1)$, since reduced χ^2 -values may be significantly affected by underestimation of σ_{phot} . Although, no galaxies were found to have large amplitude variability, we have identified two objects in these diagrams which have weak evidence for variability, which we discuss in § 8.

Aside from the possible direct detection of a “smoking gun” galaxy as a GRB source, the new data presented here on the brightest galaxies in and near GRB localizations can be used to understand minimum distance scales for cosmological GRB models. Schaefer (1992), for example, has used previous data and M31 as a standard candle to argue that the implied minimum energetics all but preclude cosmological models. Similar arguments have been put forth by Fenimore et al. (1993). We revisit this problem in Hartmann et al. (1995) where we can devote a more complete discussion to this topic.

7. PROPER MOTIONS

At the outset of this program we had hoped to obtain high-quality proper motion data similar to those obtained in the US Naval Observatory parallax and proper motion surveys (e.g., Monet et al. 1992). However, due to considerations of observing efficiency with exposure times of 60–90 minutes, many of the CCD frames in this survey were taken at large zenith distances and with poor seeing. We have not performed global proper motion solutions to the database for two reasons. First, with the relatively poor seeing and the high central image S/N needed for astrometric centroiding, we estimate that the limit-

ing magnitude for high quality astrometry at $V \leq 20$, thus covering only a small fraction of the object census. More importantly, differential color refraction errors will be large due to the large zenith distances. However, we can still place meaningful limits on proper motion detection. Since we obtained DAOPHOT profile-fitting photometry for all frames, we flagged all profile centroids that had moved five pixels or more from the fiducial coordinate list based on the fiducial frame. In fact, a number of such events occurred, but were all due to DAOPHOT being fooled by a nearby star in poor seeing conditions. There was no evidence for object movement of more than five pixels during the course of the survey. Of course, an object could have moved by much greater than five pixels and thus be missed by the photometry program entirely. But these would have been easily picked up by our search for transient objects described in § 5.

The actual proper motion detection limit is dependent upon where in time a particular fiducial frame is located during the five-year survey. Since fiducial frames were chosen solely on the basis of good seeing and sky transparency, they are randomly scattered in time between the limiting cases of being at the center or near the beginning or end of the survey. With a 5 pixel motion detection limit, a 5 year survey time baseline, and a frame scale of ≈ 0.4 arcsec pixel $^{-1}$, this implies a detection limit of $\mu \approx 1.0$ arcsec yr $^{-1}$, if the fiducial frame is at mid-survey, and $\mu \approx 0.5$ arcsec yr $^{-1}$, if at the beginning or end of the survey.

Luyten (1976) catalogs 526 stars with $\mu \geq 1.0$ arcsec yr $^{-1}$ and 3587 stars with $\mu \geq 0.5$ arcsec yr $^{-1}$ to a limiting magnitude of ≈ 17 , over a survey area covering approximately 50% of the sky. Assuming these nearby stars are uniformly distributed, we find a 0.26% and 1.74% chance of finding a $\mu \geq 1.0$ arcsec yr $^{-1}$ and $\mu \geq 0.5$ arcsec yr $^{-1}$ star, respectively, in 359 arcmin 2 area covered by this survey to a limiting magnitude of 17. Since our survey is complete to $V \approx 23$ (see Fig. 7), we extrapolate the Luyten (1976) statistics to $V = 23$ using, as an optimistic case, the upper B&S model curve displayed in Figure 7a to find a 3.6% and 24% chance of finding a $\mu \geq 1.0$ arcsec yr $^{-1}$ and $\mu \geq 0.5$ arcsec yr $^{-1}$ star, respectively. While this survey reached a magnitude and proper motion limit below which many common objects would be expected to have motions, given the above low probabilities, it is not surprising that we did not find a proper motion object within the 359 arcmin 2 area surveyed.

We note that Harrison et al. (1994a) did detect the proper motion star GL 397 in their investigation of the GBS 1028+46 field. However, this star is outside of our survey area and approximately 4 arcmin from the southern edge of the 99% GRB localization error box. We also note that Harrison et al. (1994b) found three bright stars with likely proper motions lying within 2 arcminutes of the error box of the GBS 1205+23 localization. However, the proper motions are inconsistent with these stars being within the localization error box at the time of the GRB. In any case, all three objects are brighter than our saturation limits for this field.

8. FIELD-BY-FIELD ANALYSIS

Now that we have presented the available survey data for both stars and galaxies, we turn to the objects of potential interest in each field. We state at the outset that no obvious “smoking gamma-ray guns” were found; that is, objects with colors so unusual, variability so violent, or occurrence statistics so large as to be completely inconsistent with known classes of

FIG. 21.—For all resolved galaxies in this survey, we show the photometric uncertainties discussed in § 2.7 as a function of brightness for the I , V , and B data, respectively, in panels (a)–(c) for galaxies with two or more observations. In panels (d)–(f) we plot the corresponding reduced χ^2 ($\chi^2/n - 1$) values for the I , V , and B data, respectively. The locations are shown of interesting galaxies discussed in § 8.

objects. There are a few objects with very unusual colors or which are consistent with QSOs, AGNs, or late-type objects with UV excess. Which objects we choose to discuss here is a matter of some subjectivity. We have chosen to include all objects within the localizations which might have intrinsic interest to some area of astronomy, whether or not related to GRBs. For those objects outside the localizations, observed properties and proximity to the localization are both given weight. Thus, a faint object with some evidence of variability

would be included if near the error box, but excluded if distant from it. We also note that a significant number of objects were found which lie at approximately $(U - B)$, $(B - V) = -0.4, 0.8$ and $(U - V)$, $(V - I) = 0.1, 1.0$. They are likely blue galaxies with strong U flux or QSOs. Since we cannot distinguish their nature without spectroscopy, we refer to them simply as “blue galaxies.” It is also possible that these are unresolved red/blue stellar pairs with UV excesses. We will return to this topic in the discussion section.

TABLE 6
OBJECTS OF POSSIBLE INTEREST

Object	U,B,V,I	V	$\sigma(V)$	B-V	$\sigma(B-V)$	U-B	$\sigma(U-B)$	V-I	$\sigma(V-I)$	In GRB Box?	Comments
GBS 0010-16											
96	1,3,10,6	22.10	.07	0.64	.12	-0.62	.18	1.21	.10	Yes	Blue Galaxy
76	1,5,12,10	20.30	.02	1.59	.05	0.33	.16	2.69	.02	Yes	M4 Star UV excess
52	2,2,12,8	21.67	.04	0.72	.12	-0.48	.17	1.11	.09	Yes	Blue Galaxy
61	1,3,12,9	21.49	.03	1.11	.10	-0.39	.20	1.22	.05	Yes	Star-UV excess/Gal?
GBS 0552-08											
158	1,5,15,12	20.32	.02	1.55	.04	0.33	.19	2.78	.02	No(0.15)	M4-5 Star UV excess
GBS 1028+46											
201	1,6,11,8	21.34	.05	1.22	.07	-1.21	.14	1.48	.06	No(0.9)	Res Gal UV excess
101	2,4,7,4	20.34	.07	0.34	.07	-0.22	.10	0.67	.09	Yes	Blue Galaxy Var?
10	2,4,8,2	21.76	.04	0.25	.11	-0.14	.16	0.63	.18	Yes	Blue Galaxy Var
99	1,5,6,2	22.15	.06	0.38	.07	-0.26	.18	1.17	.11	Yes	Blue Galaxy
178	1,5,9,3	22.36	.08	0.41	.12	-0.48	.21	0.89	.13	No(0.3)	Blue Galaxy
77	0,4,7,5	21.34	.03	1.73	.07	-	-	3.81	.04	Yes	M8 Star
GBS 1205+23											
130	2,5,7,4	20.47	.05	0.16	.09	-0.24	.11	0.87	.06	No(0.8)	Blue Galaxy Var
51	0,1,6,5	21.94	.04	1.87	.20	-	-	2.76	.15	Yes	Res Red Galaxy Var?
142	2,7,8,4	22.13	.04	0.46	.07	-0.56	.18	1.13	.11	Yes	Blue Galaxy
27	1,3,6,3	21.44	.02	0.51	.04	-0.72	.10	0.97	.05	Yes	Blue Galaxy
115	1,4,7,2	22.35	.04	0.40	.07	-0.69	.16	0.97	.10	Yes	Blue Galaxy
79	1,2,6,3	21.97	.07	0.56	.11	-0.59	.21	1.00	.11	No(0.15)	Blue Galaxy
GBS 1412+79											
7	0,6,14,11	20.28	.01	1.55	.02	-	-	0.87	.02	No(1.6)	Narrow SED
104	1,2,8,4	22.75	.06	0.52	.18	-1.35	.24	1.43	.17	No(1.6)	Probable QSO
OT 1809+31											
158	2,5,22,13	22.19	.02	0.48	.06	-0.44	.13	2.06	.04	NA	Red/Blue pair
163	1,5,22,6	22.23	.03	0.68	.09	-0.54	.19	1.22	.09	NA	Blue Galaxy
314	2,6,20,8	22.18	.04	0.41	.06	-0.40	.11	1.14	.08	NA	Blue Galaxy
127	2,7,25,10	21.34	.04	0.45	.05	-0.34	.06	0.73	.07	NA	Blue Galaxy
GBS 2006-22											
192	1,1,1,1	15.26	.05	1.00	.05	0.63	.07	1.10	.05	Yes	Bright Galaxy
GBS 2252-03											
183	4,2,4,4	19.32	.06	0.82	.20	0.08	.20	0.99	.10	Yes	Resolved Galaxy Var?
69	3,3,9,3	21.67	.07	0.00	.13	0.01	.14	0.57	.19	Yes	Blue Galaxy
202	1,5,9,6	20.11	.03	1.39	.05	0.55	.15	1.74	.06	Yes	M0 Star UV excess

Below we present a brief description of each object of interest, in roughly decreasing order of priority within a field. In Table 6 we present a summary of information on these objects, including the column "U, B, V, I" which represents the number of observations in each filter. The column labeled "In GRB Box?" answers whether the object lies within the IPN¹ 99% confidence localization. If it lies outside the localization, the approximate distance in arcmin to the nearest edge of the localization is given. In the finding charts (Figs. 1a-1h) the objects discussed are identified. In the color-color plots (Figs. 9-11, 20) the objects are identified, where not precluded by crowding. The few possible variable objects are identified in the variability plots (Figs. 12-19, 21).

8.1. GBS 0010-16

Object 96.—Has largest UV excess of all probable "blue galaxies" in this field. No evidence for variability. Within the GRB error box.

Object 76.—Late-type star with strong UV excess, but with only very marginal evidence for variability. ($B-V$) and ($V-I$) imply $\approx$ M4 star. Within the GRB error box.

Object 52.—Another "blue galaxy." No evidence for variability. Within the GRB error box.

Object 61.—Possible galaxy, or K5 star with some evidence of UV excess. Near center of GRB error box.

8.2. GBS 0552-08

Object 158.—Late-type star with strong UV excess, no evidence for variability. ($B-V$) and ($V-I$) imply $\approx$ M4-5 star. Outside GRB error box by 0.15 arcmin.

8.3. GBS 1028+46

Object 201.—Although this object is 0.9 arcmin from this large GRB error box, it is clearly the most interesting object in the field. It is a resolved galaxy with a large UV excess.

Objects 101, 10, 99, 178.—In this large field these objects have colors consistent with "blue galaxies," approaching that of QSOs. Object 10 has evidence for variability in the B filter. Marginal evidence for variability in V filter for Object 101. Objects 101, 10, and 99 are within the GRB error box, while object 178 is outside the error box by 0.3 arcmin.

Object 77.—While probably having nothing to do with GRBs, this is the latest type star found in the entire survey, with unreddened colors consistent with an M8 spectral type. Within GRB error box.

8.4. GBS 1205+23

Object 130.—"Blue galaxy" or QSO with evidence for variability in both B and V . Outside large GRB error box by 0.8 arcmin.

Object 51.—Very red, resolved galaxy with evidence for variability in *I* filter. In GRB error box.

Objects 142, 27, 115, 79.—In this large field these objects have colors consistent with “blue galaxies,” approaching that of QSOs. Object 142 is very near center of GRB error box. Objects 27 and 115 in GRB error box, object 79 0.15 arcmin outside.

8.5. GBS 1412+79

This GRB error box is made of highly grazing incidence annuli, thus it may not be very significant that both of the following very interesting objects are outside of the localization box.

Object 7.—This object has a very unusual *BVI* spectral energy distribution which is peaked in *V*, but much narrower than a normal star. Outside GRB error box 1.6 arcmin.

Object 104.—Very likely a QSO with strong UV excess. Outside GRB error box 1.6 arcmin.

8.6. OTS 1809+31

This OT position (Hudec 1988; Hudec et al. 1990) is likely not associated with a nearby GRB localization, as discussed in § 2.2 above. Nonetheless, we mention objects of potential astronomical interest in the field surveyed.

Object 158.—This is the red/blue pair of objects separated by 1.2 arcsec and discussed by Motch, Hudec, & Christian (1990) and which is located at the position of OT 460831. We discuss these objects in detail in Vrba et al. (1995).

Objects 163, 314, 127.—These objects have colors consistent with “blue galaxies,” approaching that of QSOs.

8.7. GBS 2006–22

Object 192.—No objects with particularly interesting colors or variability are found in this field. However, the bright galaxy (MGC 04-47-011) dominates and is located near the exact center of the GRB error box. Hurley (1985) obtained a spectrum of this galaxy with the Max Planck 2.2 m telescope. He found $z = 0.0024$, with no peculiarities in the spectrum.

8.8. GBS 2252–03

Object 183.—Fairly bright resolved galaxy located near center of GRB error box. Evidence for *B* filter variability. Normal galaxy colors.

Object 69.—“Blue galaxy.” In GRB error box.

Object 202.—Late-type star with UV excess near center of error box. ($B-V$), ($V-I$) unreddened colors imply M0 star.

Schaefer et al. (1984) reported an archival (UT 1901 Oct 04; OT 011004) flash located within the GRB error ellipse and also within our survey area. Figure 1*h* shows our calculated position of the OT and associated 3σ error ellipse which has right ascension and declination major axes of 28 arcsec and 18 arcsec, respectively. No object detected is located within the error ellipse. The “blue galaxy”/QSO candidate Object 69 lies within 1.2 arcmin of the OT ellipse, but cannot be reconciled to its position. Other objects which lie closer to the error ellipse appear not to be unusual in any way.

9. SUMMARY AND DISCUSSION

This program has provided a comprehensive photometric survey of seven IPN¹ GRB localization error boxes and of one supplemental OT field. With a detection limit of $V \approx 24$, a

completeness limit for objects with high quality photometry of $V \approx 23$ (Fig. 7), and repetitive observations of the fields to search for objects with variability totaling about 274 hours of open shutter time, the survey has produced about 79,000 calibrated photometric observations of approximately 2070 objects. This has significantly increased the parameter space examined for counterparts of GRBs over that of all previous optical searches combined.

A number of checks have been employed to test the reliability of the survey results. We have seen that the observed galaxy and star counts are consistent with previous large scale galaxy surveys and Galactic structure models. The lack of proper motion objects detected is also consistent with the known areal density of proper motion stars. Finally, the color-color diagrams produced from *UBVI* photometry reproduce well the loci of main-sequence stars and of galaxies.

The survey has revealed a number of potentially interesting objects with unusual colors and/or variability. Many of these are QSO/AGN candidates, a few late-type stars with UV excess, and a very unusual object with a spectral energy distribution narrower than that of normal stars. Despite these interesting results, the survey did not reveal an obvious GRB optical prototype counterpart. To be recognized as such, an object, if not observed during a GRB outburst, would either have to have characteristics distinguishing it from known objects, characteristics distinguishing it as a special subclass of a known object, or be so rare as to be statistically unlikely to be found consistently within GRB localizations. In light of our failure to find such an object, we must now ask what lessons can be learned from this work and how can they be applied to future non-real time counterpart searches at optical wavelengths?

Our results point out both the benefits and shortcomings of broadband photometric searches. Photometric studies with large color baselines are good at identifying potentially interesting objects at relatively faint magnitudes and with modest-sized telescopes. At the same time, the photometric data are frustratingly poor at revealing the exact nature of the objects, especially in light of the potential confusions between QSOs and red/blue unresolved stellar binaries, high- z QSOs and normal galaxies, etc. We intend to pursue vigorously follow-up spectroscopy of many of the objects we have found in this survey. It is possible that such spectroscopy will indeed identify unique objects or find a commonality of distinguishing properties amongst the candidates.

It is possible that the quiescent GRB sources are simply typically fainter than the 23–24 magnitude limits of this survey. For extragalactic objects, this seems unlikely since this brightness limit already encompasses distant galaxies and QSOs with z -values sampling the known universe. For Galactic objects this is a different story since at $V = 24$ we are only sampling to a radius of ≈ 40 pc for an M8 *V* star and even less for neutron stars. However, less luminous nearby objects, whether disk or halo population, appear to be ruled out by the BATSE observations of an isotropic GRB distribution coupled with a paucity of fainter events, indicating that GRBs come from a uniformly filled but bounded volume of space (Fishman et al. 1994; Meegan et al. 1994). Galactic objects much more luminous and thus more distant appear to be ruled out by the same combination of BATSE results (Fishman et al. 1994; Meegan et al. 1994). These considerations indicate that it is likely of little value to extend future searches below the 23–24 range of the present survey. Also, fainter surveys would be beyond the prac-

tical spectroscopic magnitude limits of even 8–10 m class telescopes.

Our intent in carrying out a long-term variability study was not to catch an object during a GRB event, since available observations and popular theoretical source models indicate recurrence times of years (if at all). Rather, we had hoped to find a degree of variability in the underlying quiescent state. In fact, we found essentially no evidence for variability of any Galactic object. Thus, future variability studies seem impractical as they would have to be carried out with much longer open shutter time and to comparable light levels. Variability studies to fainter light levels seem useless considering the previous arguments. Variability studies at detecting a lower level of variability would be dominated by chromospheric activity in late-type stars. We did find probable variability in two “blue galaxies,” but these objects would have been identified as peculiar more easily by their photometric colors. We thus conclude that spending additional telescope time for variability searches is not likely to be productive.

It is possible that the quiescent state of a GRB's underlying source is an otherwise completely normal object. In this case an identification will be impossible unless the underlying object is rare enough to be statistically linked to GRB localizations. This is probably more likely in the extragalactic case where an underlying galaxy or QSO may act as a clearly visible carrier for an otherwise common and/or unobservable source.

On the basis of the data in hand, the best candidates for relatively rare and yet ubiquitous objects within the GRB localizations are the “blue galaxies,” many of which are probably QSOs. These objects deserve attention due to the current BATSE results, which favor an extragalactic origin for GRBs. Additionally, the recent linking of an optical transient to a QSO (Vrba et al. 1994) provides additional interest in these objects. Is there any statistical link at this point between QSOs and the IPN¹ localizations? Boyle et al. (1987; Boyle, Shanks, & Peterson 1988) found QSO surface densities of 16/deg² and 37/deg² at $B \leq 20.0$ mag and $B \leq 20.9$ mag, respectively. More recently He & Chen (1993) reported QSO densities only 28% as large as those of Boyle et al. (1987, 1988). Extrapolating these unreconciled results to $B \approx V \approx 22$ mag, the approximate detection limit for QSOs in this survey, implies a QSO surface density range of approximately 28 to 100 QSOs/deg².

Of the total 359 arcmin² covered by this survey, we exclude the 86.7 arcmin² associated with the low Galactic latitude fields GBS 0552–08 and GBS 2006–22. Despite the fact that the bright galaxy MGC 04-47-011 lies near the center of the GBS 2006–22 localization, Figures 7 and 8 show no excess of objects for these fields above that of the expected Galactic stellar population. Hence, these lines of sight appear not to probe deeply beyond the Galaxy. The OTS 1809+31 field (32.5 arcmin²) is additionally excluded since it is not associated with a known GRB. Based on the above range QSO densities, two to seven QSOs are expected within the total 240 arcmin² of the remaining five fields.

In Table 6 we identify 13 “blue galaxy” QSO candidates in the five fields based on anomalous $(U-V)$ versus $(V-I)$ colors. However, as mentioned previously, the QSO region of the $(U-V)/(V-I)$ diagram will be polluted by unresolved red/blue stellar binaries. In a large-scale search for QSOs near globular clusters using the same telescope, filters and CCDs as employed in this study, Guetter (1994) found, after spectroscopic study, that only 60% to 70% of QSO candidates identified with the $(U-V)/(V-I)$ discriminant were actually QSOs.

Applying a 65% “hit rate” to the 13 QSO candidates in the five fields yields an estimated eight true QSOs. We conclude that our observations are consistent with a complete sample of QSOs within the survey area to a magnitude of ≈ 22 .

We now direct our attention to the 134 arcmin² of GBS error boxes in the five high Galactic latitude fields. There are nine QSO candidates in the five boxes, of which $\approx 65\%$, i.e., 5.9, are expected to be actual QSOs. If QSOs and GRBs are correlated, the candidates (and actual QSOs) must be distributed appropriately amongst the error boxes. Using the Kolmogorov-Smirnov test, the hypothesis that the nine candidates are uniformly distributed amongst the error boxes in proportion to their sizes cannot be rejected at the 80% confidence level. The proposed correlation also requires that

$$\Pi_B = \lim_{A_B \rightarrow 0} (Q_{\text{obs}} - \rho_{\text{QSO}} A_B) = 1, \quad (15)$$

and hence,

$$\Pi = \sum_{B=1}^N \Pi_B = N \quad (16)$$

where for each GBS error box B , Q_{obs} is the number of observed QSOs deg⁻², ρ_{QSO} is the average surface density of QSOs deg⁻², A_B is the area in deg² of box B , and N is the number of GBS boxes considered. Equation (15) is most efficient when applied to GBS boxes with $\rho_{\text{QSO}} A_B \ll 1$. Unfortunately, the present data do not generally meet this criterion, especially for the Boyle et al. (1987, 1988) densities, where the average $\rho_{\text{QSO}} A_B = 0.75$. In lieu of a rigorous application of equation (15) we utilize equation (16) and evaluate it for the five fields combined and at the extremes of the QSO density range. The Boyle et al. (1987, 1988) densities yield $\Pi = (5.9-3.7) = 2.2_{-3.3}^{+2.9} < 5$, where the upper and lower errors are the 95% and 40% Poisson probabilities, respectively. These errors are understated since no uncertainty is assigned to the 65 percent “hit rate” factor. For QSO densities as high as those of Boyle et al. we conclude that there is currently no statistically significant evidence for a QSO/GRB correlation. At the lower extreme, the He & Chen (1993) densities produce $\Pi = (5.9-1.0) = 4.9_{-1.0}^{+1.4} \approx 5$ —a tantalizing suggestion of a QSO/GRB correlation.

Much, if not all, of the uncertainty in understanding which candidates are actual QSOs will be dispelled by spectroscopic examination. The large range of possible QSO densities is less easily constrained. However, as seen in equation (15), a QSO/GRB correlation can be detected against a background of arbitrarily large QSO density if the GBS positions are sufficiently localized. Fortunately, such localizations have recently become available from the Third Interplanetary Network (Hurley 1993). Of 19 new GRB localizations, 11 have error box sizes of ≤ 10 arcmin² and 14 with ≤ 15 arcmin², with mean sizes, respectively, of 4.0 and 5.8 arcmin². For mean error box sizes of 4.0 arcmin² this implies QSO background rates per localization of $\rho_{\text{QSO}} A_B = 0.11-0.03$, respectively, for Boyle et al. (1987, 1988) and He & Chen (1993) statistics.

We are actively pursuing deep $UBVI$ CCD searches of these fields much in the same manner as described herein for the IPN¹ survey, except that we are not providing long term coverage of the fields to search for variability. While we will carefully cull the data for any object which might appear promising, the calculations above indicate that at least the question of QSO involvement may indeed be resolved by the new observations. It is our intent to continue to provide deep photometric

surveys of future small localizations as they become available. Finally, we will continue deep searches of the small targets provided by archival optical transients (Hudec 1993). Our discovery of a QSO (Vrba et al. 1994) likely associated with an optical transient near GB 910219 indicates that this is an exciting area for future research whether or not related to the GRB phenomenon.

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