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THE SOURCES OF GAMMA-RAY BURSTS AND THEIR CONNECTIONS WITH QSOs AND ACTIVE GALAXIES

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ABSTRACT

It is shown that the redshifts z_o of γ-ray burst (GRB) sources, where they have been measured, together with the redshifts for seven quasars (QSOs) that lie very close to the positions of the unidentified sources GRB 990625, 000210, 001105 (two QSOs), 940720, 991217, and 990506, show a remarkable tendency to cluster about several of the periodic redshift peaks previously established for QSOs at $z = 0.061$, 0.30, 0.60, 0.96, 1.41, 1.96, 2.63, 3.44, and 4.45. In 1971, Karlsson showed that these peaks lie in a series with $\Delta \log(1 + z) = 0.089$. Out of a total of 32 currently known redshifts of GRBs, afterglows, or QSOs very close to burst positions, two are very close to 0.30, three are close to 0.60, nine are equal to or very close to 0.96, three are very close to 1.41, six are close to 1.96, two are close to 3.44, and one is very close to 4.45. Statistical tests by W. Napier show that the observed redshifts z_o showed periodicity at the 98% confidence level. In addition, very close to the positions of two bursts GRB 990625 and GRB 001105, many QSOs with redshifts close to the peak values have been found. Since $z_o = [(1 + z_c)(1 + z_{\rm D})(1 + z_i) - 1]$, where z_c, $z_{\rm D}$, and z_i are the cosmological, Doppler, and intrinsic components of the observed redshift z_o, the existence of these peaks suggests that $z_o \simeq z_i$, so that both z_c and $z_{\rm D}$ are very much less than z_o. However, while the observed values of z_o are very close to the corresponding values of z_i, in most cases $z_o > z_i$, suggesting that in most cases z_c is greater than it was found to be in earlier samples of X-ray QSOs that appear to be ejected from bright galaxies. It appears likely, therefore, that the GRB sources, like the QSOs, are ejected from active galaxies, most of which have comparatively small cosmological redshifts $0.02 \leq z_c \leq 0.1$, thus suggesting that the distances of most of the GRB sources are $\leq$500 Mpc. A possible example of an active galaxy that has given rise to such phenomena is UGC 12348 ($z_i = 0.03$). This galaxy has two GRB sources and three QSOs with measured redshifts z_o that lie very close to intrinsic redshift peaks all lying within 1° of it. Among these five objects, the QSO at $z = 3.7$ lies inside the error box for the unidentified burst GRB 991217.

Subject headings: cosmology: miscellaneous — gamma rays: bursts

1. INTRODUCTION

There are several parallels between the sequence of discoveries involving γ-ray bursts (GRBs) and those concerning discrete radio sources.

The first systematic detections of bright radio sources suggested that they were distributed roughly isotropically. Since at that time, in the 1950s, it was already thought that the radiation mechanism was an incoherent synchrotron process, or possibly a coherent plasma process, and that stars were involved, the sources were deduced to be flare stars close enough to the Sun that their distribution was isotropic. The alternative hypothesis, that the distribution of radio sources on the sky could be as well understood as meaning that they are extragalactic and lie at great distances, was suggested but was not taken seriously at that time.

Interpretation of the GRB discoveries followed a somewhat similar path. By the time that ~500 bursts had been recorded, it was clear that the distribution was uniform according to the $V/V_{\rm max}$ test and isotropic on the sky. However, a great deal of effort had been devoted by theorists to try to understand the physics of the bursts by supposing that they take place on neutron stars. The observational arguments for this point of view were based on the very small source sizes based on the very rapid fluctuations, lines in absorption that were attributed to cyclotron lines in 10^{12} G magnetic fields, and emission lines in the 380–500 keV range attributed to gravitationally redshifted electron-positron annihilation radiation.

In both fields the breakthrough came only after *optical* identifications of the sources had been made. In the case of the radio sources, an accurate position for the strongest source in Cygnus, Cygnus A, led to its identification with an object with a redshift of $z = 0.057$. This object became the prototype radio galaxy. Further optical identifications showed that the majority of the discrete radio sources were of extragalactic origin, arising in either elliptical galaxies, strong emission-line systems generally thought to be contained in elliptical galaxies, or QSOs, sometimes called quasars or active galactic nuclei (AGNs). The first QSOs were identified from radio source positions, although we now know that most of them are only very weak radio emitters.

The discovery that the GRBs also have an extragalactic origin came only after the first *BeppoSAX* identification of an optical object was made and a redshift was measured. By now, a number of burst sources have been identified and have had redshifts measured. The fact that the sources are extragalactic has immediately led to the conclusion that the energy released in the burst is much larger than that which can be explained in terms of the original neutron star models. The classes of models that are now being explored are the so-called fireball models and models involving extreme supernova events. In both the radio source identifications and the GRB identifications, the key questions that need to

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be answered are what the nature is of the optical sources that give rise to these phenomena and how far away they are. For the radio sources, the morphology, optical spectra, and redshifts have been the keys. As far as the radio sources are concerned, more and more of the sources identified with high-redshift QSOs showed several phenomena that suggested that perhaps the redshifts of these objects contain components that are not attributable to the expansion of the universe. It was immediately realized that if this were correct, it would mean that the QSOs are not as far away as they would be if it were assumed that the redshifts are completely of cosmological origin (Hoyle & Burbidge 1966). While this point of view has never been generally accepted, the evidence in its favor has continued to grow.

The strongest evidence is that the observed redshifts of QSOs are made up of three components: z_c, a cosmological component, $z_{\rm D}$, a Doppler component that is a measure of the line-of-sight component of local velocity of the QSO, which can be either positive or negative, and z_i, an intrinsic component whose origin is not understood theoretically but is basic to the physics of the QSO. The observed redshift z_o is given by the equation

$$(1+z_o) = (1+z_c)(1+z_{\rm D})(1+z_i) \ . \qquad (1)$$

The evidence has come from two kinds of observations. The first is that there is much direct evidence that many QSOs are physically associated with galaxies with much smaller redshifts, so that for these cases $z_i \gg z_c$. This evidence is both statistical and morphological and has been described in many papers (Arp 1967; Arp 1987, 1999; Burbidge et al. 1971; Burbidge et al. 1990; Burbidge 1979, 1996). It stems from the fact that there are far more bright QSOs with large redshifts very near to bright galaxies with very small redshifts than is expected by accident. It appears that active galaxies, which are nearly all spirals, eject QSOs with much higher redshifts. This was first discovered in samples using radio-emitting QSOs (e.g., Burbidge et al. 1971). More generally, the effect has been found in larger samples (e.g., Burbidge et al. 1990). The effect has also been found more recently for X-ray–emitting QSOs, many of which cluster about bright active galaxies (Pietsch et al. 1994; Burbidge 1995, 1997, 1999; Radecke 1997; Chu et al. 1998; Arp 1999; Arp et al. 2001). However, in some situations, the value of z_i may be very small. In some low-redshift QSOs, $0 < z_i < z_c$, as is seen from the work on the fuzz around the QSOs, which in some cases is due to normal galaxies (J. Miller 2000, private communication).

The second piece of evidence showing that z_i is often dominant is that peaks and periodicities are found in the QSO redshift distribution, and these are not due to optical or spectroscopic selection effects. Initially, redshift peaks at $z_o = 1.96$ and 0.061 were found in 1967 and 1968 (Burbidge & Burbidge 1967; Burbidge 1968), and by 1977, peaks had also appeared at $z_o = 0.30$, 0.60, 0.96, and 1.41 (e.g., Burbidge 1978). Karlsson (1971) showed that the peaks are periodic with $\Delta \log(1+z) = 0.089$. In 1990 he showed that QSOs lying close to bright galaxies strongly showed the effect (Karlsson 1990). This relation predicts that peaks should appear at higher redshifts $z_o = 2.63$, 3.44, 4.45, 5.71, etc. In a recent paper using new QSO samples, peaks up to 4.45 have appeared (Burbidge & Napier 2001), and it has been shown that the probability that the peaks appear accidentally in these samples is extremely small ($\sim 10^{-5}$). It should be stressed that periodic intrinsic redshift peaks will be impossible to find in large optically chosen samples of QSOs such as the 2dF QSO Redshift (2QZ) survey or the Sloan survey, simply because in those surveys QSOs with a considerable range of cosmological redshifts are present and a small dispersion in z_c will smear out the peaks associated with z_i. To use samples from these surveys, it would be necessary to identify the parent galaxies and measure their redshifts, or at least isolate using a statistical analysis a likely parent population of spiral galaxies.

The QSO samples must be carefully chosen, from sources discovered by techniques other than large optical surveys. The effect was first discovered in bright QSOs originally identified as radio sources. Until the late 1970s, the majority of QSOs had been identified from radio positions. The most recent samples involve either QSOs identified first as X-ray–emitting QSOs clustered about active galaxies or pairs or multiple QSOs chosen *because* they are very close together. No optical criteria are involved.

The model for QSOs that emerges from all of these data and analyses is that QSOs are ejected from the nuclei of spiral galaxies. For the nearby (bright) QSOs, $z_c \ll 1$, and a large part of their redshifts are intrinsic. Putting $z_c \ll 1$ in equation (1),

$$(1+z_{\rm obs}) = (1+z_i)(1+z_{\rm D}) \ . \qquad (2)$$

For the sample of X-ray–emitting QSOs discussed by Burbidge & Napier (2001), it was shown that $|\bar{z}_{\rm D}| \approx 0.04$. Does this model have any connection with the origin of the GRB sources? In the following sections we present evidence that it does.

2. ASSOCIATIONS OF GRBs WITH QSOs

By the summer of 1999, accurate positions for a number of GRB sources and afterglows in X-ray, optical, or radio fluxes had been detected, and redshifts had been measured for eight of them (e.g., van Paradijs, Kouveliotou, & Wijers 2000). At that time, I noticed that three of them, GRBs 970508, 971214, and 980703, had redshifts almost exactly on the intrinsic redshift peaks 0.96 and 3.44 that had been found in other samples of QSOs (Karlsson 1971; Burbidge & Napier 2001).

The optical spectra of the sources from which the redshifts are measured show either single or in some cases several emission lines of the type that are associated with gas excited by hot stars or nonthermal sources, or they show narrow absorption lines of Mg II, Fe II, and other ions, which are very similar to absorption systems seen in the spectra of QSOs. This together with the fact that some of the sources are slightly extended has led to the conclusion that in each case, what has been detected is either the host galaxy in which the burst occurred or an intervening absorbing galaxy or cloud. It is usually argued that the host galaxies are so-called starburst galaxies, in which the rate of massive star formation is high. The observational case for this has recently been given by Bloom, Kulkarni, & Djorgovski (2002). Seen from this point of view, there is no reason to doubt that the redshifts are truly cosmological in origin, since the redshift phenomena that we described earlier in QSOs, which led to the conclusion that they often have dominant components of noncosmological origin, have not been found in normal galaxies, nor do we question the interpretation of the Hubble relation for normal galaxies as evidence for cosmological expansion. At the same time, while the γ-ray sources often arise in what are called host galaxies, many assumptions have had to be made about stars in them and their state of evolution to interpret them in this way.

Thus, since in three cases the "intrinsic" redshifts appeared, I thought it was worthwhile to collect more data to see if there might be other pointers to the nature of the burst sources. Bearing in mind that except for GRB 980425 the distribution of the burst sources suggests that they lie farther away than the local supercluster of galaxies, I concluded that if the burst sources have redshifts with the same origin as the observed QSO redshifts, where an intrinsic component dominates, the parent galaxies will have small but nonnegligible cosmological redshifts. From equation (1), this means that z_o will in general be slightly greater than z_i, although this may not always be the case, since z_D can be both positive and negative.

In addition, if the burst sources are objects ejected from active galaxies, they may well be accompanied by QSOs or be QSOs at a different state of evolution that have also been ejected from the same galaxies. Thus, I decided to look for QSOs close to burst positions, whether or not the redshifts of the burst sources have been determined.

In the following sections I attempt to show that the observational evidence suggests that the GRB sources *are* closely related to QSOs and that they are also probably ejected from parent galaxies and explode when they have traveled some distance from the parent galaxy.

3. GRB SOURCE POSITIONS COMPARED WITH QSO AND AGN POSITIONS

According to the 2002 compilation of J. Greiner,[2] there are approximately 140 GRBs that have had positions determined so that the error boxes for them or for the afterglows have dimensions $\lesssim 10'$. Of these, 22 have been identified with optical objects for which redshifts have been determined.

I have taken the complete list of positions and have compared it with the positions of QSOs and AGNs in the catalog recently compiled by Véron-Cetty & Véron (2001), which contains about 29,000 QSOs and AGNs. For the majority of the GRBs in the list, there are no QSOs known that lie within $\sim 1°$ of the burst positions. However, for 34 GRBs, there are known QSOs or AGNs lying at distances $\leq 1°$. The results of this search are given in detail in Table 1.

It is not surprising that there are no cataloged objects close to the majority of the GRB positions. This is because most of the sky has not been surveyed for QSOs and AGNs. The more important question is whether or not any of the pairings shown in Table 1 are statistically significant. Three results are apparent from Table 1.

3.1. *Statistical Associations of Known QSOs with GRB Positions*

There are six GRBs, 990625, 000210, 960720, 001105, 991217, and 990506, that together have a total of seven QSOs lying within $5'$ of the positions of the centers of the error boxes. Are these apparent associations likely to be accidental? Assuming that the QSOs are distributed at random with uniform density on the sky, the number of accidental close pairs is given by

$$n = 8.64 \times 10^{-4} \Gamma \theta^2 N \ , \qquad (3)$$

where Γ is the surface density of QSOs (deg^{-2}), N is the number of burst positions examined, and θ is the angular separation measured in arcminutes.

In limited regions of the sky, Γ is well established and ranges from ~ 3 deg^{-2} between $m = 18$ and 19 to ~ 20 deg^{-2} at $m = 20$ (Boyle et al. 1990, 2000; Kilkenny et al. 1997). If we set $\Gamma = 20$ and $\theta = 5'$, we find that $n = 0.432N$. If we set $N \simeq 140$, we might well conclude that these are accidental configurations. However, the calculation done in this way grossly overestimates the number expected by accident, since the surveys of the sky for QSOs are very incomplete. This can be seen from the plots of Hewitt & Burbidge (1993) and also by comparing the total number of QSOs and AGNs with redshifts now known, about 29,000, with the total number of QSOs over the whole sky, about 10^6 to 20 mag. Thus, a correction factor of the order of $30,000/10^6 = 0.03$ can conservatively be applied to the calculated value of n. Using these figures, the number of chance juxtapositions expected is about 1.8, compared to the seven pairs found. While there are clearly uncertainties in this conclusion, since the magnitudes of the seven QSOs are 20.2, 18.5, 19.9, 20.2, 19.4, and 21.7 mag, and one not known, we conclude that this result is significant and that the associations are real.

A referee has suggested that I elaborate on this point, and this is done in following paragraphs.

The fact that the total number of objects in the Véron catalog is about 29,000 means that only a very small fraction of the sky has so far been surveyed for QSOs down to 20 mag. How have the catalogs been made up? As was shown in detail by Hewitt & Burbidge (1993), when only 7300 QSOs were known, 43 separate surveys were involved, 17 of them based on catalogs of radio positions. The earliest surveys came from the identification of QSOs with strong radio sources in the Third Cambridge (3C), 4C, and Parkes catalogs of radio sources. These radio surveys covered wide areas of the sky, but the QSOs that were identified tended to be the brighter ones, which are much rarer. When the first optical surveys for QSOs were carried out, much higher surface densities of QSOs were found, and it was concluded that only about one QSO in 50 is a strong radio source. However, the mere fact that the optically identified QSOs are fainter and much more common means that it is much more laborious to identify QSOs (since individual spectra have to be obtained for each candidate). This in turn means that the survey areas covered are much smaller than was the case when the QSOs were first identified as radio sources.

More recently, many QSOs have been identified from X-ray source catalogs, and this has led to QSOs being found over a wide area of the sky, but as was the case for the radio identifications, there are no detailed optical surveys covering these large regions. Most of the objects in the Véron catalog come from detailed optical surveys that, as we have just pointed out, are necessarily carried out over very small areas. Thus, while about 50 catalogs contribute to the makeup of the Véron list, most of them, as was the case for the Hewitt & Burbidge (1993) list, contain only a few

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[2] See http://www.mpe.mpg.de/~jcg/grbgen.html.

TABLE 1

QSOs AND AGNs NEAR GRBs

	POSITION (J2000.0)					
BURST	α	δ	COMPANION	m	z	SEPARATION (arcmin)
990625:	00 26 34	−31 12 00				
2QZ J002643−3108	00 26 43.2	−31 08 37	QSO	20.22	1.344	3.8
2QZ J002611−3102	00 26 11.7	−31 02 26	QSO	20.69	0.948	11.1
2QZ J002619−3106	00 26 19.3	−31 06 22	QSO	20.85	1.413	6.7
2QZ J002355−3103	00 23 55.7	−31 03 34	QSO	20.75	0.215	40.5
2QZ J002502−3124	00 25 02.7	−31 24 42	QSO	19.55	1.497	26.1
2QZ J002506−3104	00 25 06.3	−31 04 05	QSO	20.41	0.665	23.3
2QZ J002728−3106	00 27 28.6	−31 06 34	QSO	20.79	1.314	14.7
2QZ J002743−3107	00 27 43.1	−31 07 36	QSO	20.23	2.051	17.8
2QZ J002759−3102	00 27 59.2	−31 02 56	QSO	20.73	0.768	23.1
011019:	00 42 50.23	−12 26 58				
RXS J00424−1335	00 42 27.1	−13 35 33	QSO	17.1	0.291	68.8
001005:	01 24 05	+25 00 00				
B20119+24	01 22 38.8	+25 02 32	QSO	18.6	2.025	19.7
000210:	01 59 15	−40 40 00				
CTS B19.09	01 59 29.9	−40 43 25	QSO	18.5	2.02	4.4
000911:	02 18 42	+07 48 00				
Mrk 1400	02 20 13.8	+08 12 20	AGN	15.27	0.029	33.3
0216+0803	02 18 57.3	+08 17 28	QSO	18.1	2.99	29.7
990217:	03 02 52	−53 06 00				
CTS HS25.02	03 04 50.3	−53 19 41	QSO	18.5	2.27	22.4
980329:	07 02 41	+38 50 18				
B30701+392	07 04 31.3	+39 11 23	QSO	18.7	1.283	29.8
020127:	08 15 06	+36 44 00				
B20812+36	08 15 26	+36 35 15	QSO	19.0	1.025	9.6
000730B:	08 25 46	+60 04 00				
RXS J08252+6011	08 25 13.1	+60 11 47	AGN	15.82	0.12	8.8
SBS 0818+602	08 21 59.4	+60 03 21	QSO	17.7	1.523	28.2
990520:	08 35 05	+51 18 00				
87GB 08361+5112	08 39 46.1	+51 12 00	QSO	18.45	4.41	44.4
980613:	10 17 46	+71 29 54				
NGC 3147	10 16 53.2	+73 24 12	Sey 2	12.65	0.01	114.0
00623:	11 15 41	+10 42 00				
RX J111244+1101	11 12 24.2	+11 01 03	QSO	18	0.636	52.6
011211:	11 15 16	−21 56 00				
PKS 1114−220	11 16 54.5	−22 16 52	QSO	20.2	2.282	30.9
990506:	11 54 50	−26 40 35				
CTS M07.12	11 52 03.1	−26 37 24	QSO	19.2	2.04	27.0
971214:	11 56 30	+65 12 00				
4C 65.13	11 55 17.9	+65 39 17	QSO	18.1	1.199	28.3
000418:	12 25 21	+20 05 00				
RX J12257+2056	12 25 41.9	+20 55 04	QSO	16.5	0.335	50.3
001105:	13 01 54	+35 29 00				
BVF 161	13 01 47	+35 20 31	QSO	19.43	2.04	2.1
WEE 91	13 01 32.1	+35 27 29	QSO	21.7	2.03	4.7
BVF 164	13 01 53.5	+35 54 05	QSO	19.27	0.69	25.1
WEE 93	13 01 54.5	+35 14 59	QSO	20	1.9	14.0
BVF 166	13 02 00.2	+35 39 48	QSO	18.72	1.23	10.8
BVF 170	13 02 08.7	+35 47 16	QSO	19.21	1.76	18.5
BVF 175	13 02 21	+35 48 47	QSO	19.73	0.68	20.5
B234	13 03 03.3	+35 51 28	QSO	17.52	0.06	26.5
BVF 202	13 03 11.4	+35 56 34	QSO	19.76	1.93	31.8
020405:	13 58 10	−31 23 00				
IRAS 3550−3142	13 57 55.3	−31 57 11	AGN		0.189	34.4
000630:	14 47 15	+41 13 00				
4C 41.28	14 46 26.8	+41 33 18	QSO	18.2	0.675	22.2
970111:	15 28 15	+19 36 18				
ISAX J15288+1939	15 28 49	+19 38 51	QSO	20.7	0.175	8.2
000615:	15 32 34	+73 48 00				
UGC 9944	15 35 47.9	+73 27 02	Sey 2	14.9	0.025	25.1

TABLE 1—*Continued*

	Position (J2000.0)					
Burst	α	δ	Companion	m	z	Separation (arcmin)
991208:	16 33 55	+46 26 00				
Q1628+4629	16 29 39.5	+46 23 24	QSO	18.4	0.109	44.1
Q1629+4630	16 31 07.5	+46 23 45	QSO	20.28	0.19	29.0
Q1630+4633	16 32 20.8	+46 26 52	QSO	19.66	0.25	16.3
Q1631+4628	16 32 53.3	+46 21 45	QSO	18.25	0.031	11.5
Q1635+4635	16 36 58.5	+46 29 27	QSO	19.79	1.486	31.8
000926:	17 04 15	+51 46 00				
NPM 1G+52.0273	17 00 27.2	+51 59 11	AGN	16.89	0.048	29.0
001019:	17 11 44	+35 20 00				
FIRST J1713+3523	17 13 04.5	+35 23 54	AGN	16.84	0.083	16.8
940720:	17 30 37	+49 05 48				
4C 49.29	17 30 44.5	+49 06 26	QSO	19.9	1.038	2.3
17252+499	17 26 29.5	+49 55 17	QSO	19.9	1.9	63.9
2E 1726+4955	17 27 16.4	+49 52 58	QSO	14.3	0.815	57.5
17272+499	17 28 32.2	+49 54 10.1	QSO	19.3	1.9	52.5
IRAS 17343+4920	17 36 10.1	+49 18 30	AGN	15.8	0.075	56.2
010104:	17 49 46	+18 14 00				
NGC 6500	17 55 59.8	+18 20 19	Sey 3	12.54	0.01	89.0
000812	18 08 44	+45 51 00				
S4 1806+45	18 08 22	+45 42 21	QSO	19.3	0.83	9.5
010119:	18 53 50	+12 41 00				
Padova 1	18 52 02.1	+11 52 41	Sey 1	15	0.009	27.7
980425:	19 34 54	−52 49 54				
ESO 184-G82	19 35 03	−52 50 45	Galaxy		0.0085	1.6
980515:	21 18 04	−67 14 54				
2E 2111−6749	21 15 56.6	−67 35 22	QSO	18.9	0.549	23.9
001120:	22 18 28	+01 06 00				
FIRST J22181+05522	22 18 06.7	+00 52 23	QSO	17.7	1.27	14.6
SDSS J2208+84C019	22 20 50.8	+00 19 58	QSO	21.67	4.68	38.3
010921:	22 55 59.9	+40 55 53				
UGC 12282	22 58 55.4	+40 55 58	Sey 1.9	14.7	0.017	33.1
991217:	23 03 15	+00 15 00				
UGC 12348	23 05 18.9	+00 11 00	Sey 2	15.3	0.03	31.2
SDSSp J2303+016	23 03 23.7	+00 16 15	QSO	20.24	3.7	2.5
000519:	23 04 39	+01 10 00				
UGC 12348	23 05 18.9	+00 11 00	Sey 2	15.3	0.03	59.8
PC 230+0021	23 04 14.6	+00 37 39	QSO	22.45	2.647	32.9
FIRST J23054+0036	23 05 24.5	+00 36 24	QSO	19.42	0.608	35.5

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

hundred objects. On the other hand, for example, about 10,000 QSOs in the Véron list come from the 2QZ survey made using the Two-Degree Field (2dF) 400 fiber multiobject spectrograph at the Anglo-Australian Telescope.[3] The total area covered in that survey is 740 $\deg^2$, or about 1.8% of the sky. About 25,000 QSOs are predicted to be found in the magnitude range $18.25 < m < 20.85$, and the 10,000 in the current Véron catalog means that only a fraction of this 1.8% of the sky is so far available. About 2000 come from the Large Bright Quasar Survey (Hewett, Foltz, & Chaffee 1995). Thus, if we allow for the fact that out of the ~29,000 objects about 3000 are active galaxies with very small redshifts that we believe are largely cosmological in origin, about half of the QSOs are contained in two optical surveys covering only about 2% of the sky.

The content of Table 1 clearly shows this effect of the patchiness of the optical surveys for QSOs.

Thus, if we exclude the cases in which the only object within ~1° of the GRB *is* an active galaxy, there are only 28 out of 140 burst positions in which even a single QSO is found, i.e., about 20%. In three cases, the sole QSO listed is a 4C radio source or a Parkes radio source.

However, it is also immediately obvious that in the few cases in Table 1 in which a burst position is in a region that has been surveyed in more detail, as is the case for GRBs 990625 and 001105, many QSOs are present, and four of the seven QSOs that lie within 5′ of the burst positions come from these fields.

All of these arguments lead us to conclude that the number of QSOs lying very close to burst positions can reasonably be compared with the number expected by accident after a correction factor of 0.03 is applied, this factor being based on the total number of QSOs so far detected compared to the number expected.

We now turn to a second argument that we believe adds to the significance of this result. This is associated with the numerical values of the redshifts of the QSOs very close to

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[3] See http://www.2dfquasar.org.

the burst positions. If they were accidental associations, the QSOs could have any value of redshift, but they do not.

3.2. *The Redshifts of the QSOs Very Close to GRB Positions*

In Table 2 we list the redshifts of the QSOs lying very close to GRB positions and compare them with the intrinsic redshift peaks nearest to them, which were previously determined from earlier samples (e.g., Burbidge & Napier 2001). With one exception, the differences in Table 2 are less than 0.1. The conclusion is quite remarkable. Of the 11 QSOs listed, nine lie very close indeed to the intrinsic redshift peaks.

As was mentioned above, the regions around two of the burst positions, GRBs 990625 and 971214, have been surveyed in detail, and in Table 1 nine QSOs are found close to GRB 990625 and also nine QSOs close to GRB 001105.

In each case, seven of the nine have observed redshifts z_o within 0.1 of the intrinsic peak values. This adds further weight to our hypothesis. It suggests that the parent galaxy, which remains unidentified, has a very small cosmological redshift and has given rise to many QSOs and at least one GRB source.

It is very easy to make an estimate of the combination of cosmological and Doppler redshift components, since from equation (1) we have that

$$z_o \simeq z_i(1 + z_c + z_{\rm D}) + (z_c + z_{\rm D}) \ , \tag{4}$$

where we have neglected the products $(z_c z_{\rm D})$ and $(z_i z_c z_{\rm D})$. Earlier we had deduced from the sample of X-ray–emitting QSOs associated with active galaxies discussed by Burbidge & Napier (2001) that for that sample, $|\bar{z}_{\rm D}| \simeq 0.04$, i.e., the ejection speeds of the QSOs from the galaxies average about 12,000 km $\rm s^{-1}$ (both redshifts and blueshifts).

Let us consider some illustrative examples:

1. If $z_c = |\bar{z}_{\rm D}|$, then from equation (2), if $z_{\rm D}$ is positive,

$$z_o = z_i(1 + 2z_c) + 2z_c \ ,$$

and if $z_{\rm D}$ is negative,

$$z_o = z_i \ .$$

Thus, for both cases $z_o \geq z_i$.

TABLE 2

QSOs Very Close to Burst Positions

Burst	Separation between QSO and Burst Position (arcmin)	z_o	z_i	$z_c + z_d$
990625	3.8	1.344	1.41	−0.027
	6.7	1.413	1.41	+0.001
	11.1	0.948	0.96	−0.006
000210	4.4	2.02	1.96	+0.020
020127	9.6	1.025	0.96	+0.033
001105	2.1	2.04	1.96	+0.027
	4.7	2.03	1.96	+0.024
970111	8.2	0.175	0.30	−0.096
940720	2.3	1.038	0.96	+0.040
000812	9.5	0.83	0.96	−0.066
991217	2.5	3.7	3.44	+0.058
990506	0.5	0.273	0.30	−0.021

2. If $z_i = 2|\bar{z}_{\rm D}|$, then for $z_{\rm D}$ positive,

$$z_o = z_i(1 + 1.5z_c) + 1.5z_c \ .$$

If $z_{\rm D}$ is negative,

$$z_o = z_i(1 + 1.5z_c) + 0.5z_c \ .$$

Thus, for both cases $z_o \geq z_i$.

3. If $z_c = 0.5|\bar{z}_{\rm D}|$, then

$$z_o = z_i(1 + 3z_c) + z_c$$

for $z_{\rm D}$ positive, but for $z_{\rm D}$ negative,

$$z_o = z_i(1 - z_c) - z_c \ ,$$

and for this case $z_o < z_i$.

We do not know the values of z_c or $z_{\rm D}$ for any of the QSOs in Table 2. Thus, we can only make estimates of the range of z_c among them by looking at the relative number of positive and negative values of $(z_o - z_i)$.

We do this in § 4 when we combine these results with the lists of redshifts of identified bursts.

3.3. *The Remarkable Configuration Involving GRBs 991217 and 000519*

From Table 1 we see that the positions of GRBs 991217 and 000519 are separated by only $59'$. We can ask how likely it is that this is an accidental effect. Using equation (3), setting the surface density of GRBs to be $\approx(140/4 \times 10^4) = 3.5 \times 10^{-3}$ $\rm deg^{-2}$, and assuming a separation of 1°, we find that about one pair might be expected by chance. Thus, this configuration could be accidental. However, both of these bursts lie within 1° of the bright AGN UGC 12348 (15.3 mag). Active galaxies as bright as this are themselves very rare, with a surface density on the sky of no more than 3×10^{-2} $\rm deg^{-2}$. Thus, the triple configuration is unlikely to be accidental. Thus, it is likely that UGC 12348 is the parent galaxy of both bursts, with a cosmological redshift $z_c = 0.03$ (e.g., Fig. 1).

This is just the kind of parent galaxy that has been found to be associated with the sample of X-ray QSOs previously discussed (Burbidge & Napier 2001; Burbidge 2001), although it is at a greater distance. Studies of many of the individual cases in this sample (Arp et al. 2001; Burbidge 1995, 1997, 1999) suggest that the parent AGNs are Seyfert galaxies with redshifts of cosmological origin.

From Table 1 we see that also in this remarkable system are three QSOs that lie close to the two burst sources and UGC 12348. One of them, SDSSp J2303+016, lies only $2'.5$ from one of the GRB sources, 991217, and is included in Table 2. Finally, we emphasize that all three of the QSOs have values of z_o very close to the intrinsic redshift values previously predicted. The values are $z_o = 0.608$ $(z_i = 0.60)$, $z_o = 2.647$ $(z_i = 2.63)$, and $z_o = 3.7$ $(z_i = 3.44)$. If we assume that UGC 12348 is the parent galaxy of the bursts *and* the QSOs and put $z_c = 0.03$, we calculate the line-of-sight component and ejection speeds of the QSOs to be +1500 km $\rm s^{-1}$ (FIRST J23054+0036), +1400 km $\rm s^{-1}$ (PC 230+0021), and +17,600 km $\rm s^{-1}$ (SDSSp J2303+016).

These values of $cz_{\rm D}$ can be compared with those found for a set of X-ray–emitting QSOs associated with active galaxies studied by Burbidge & Napier (2001). In this case also, we know the values of both z_i and z_c, the latter being the parent

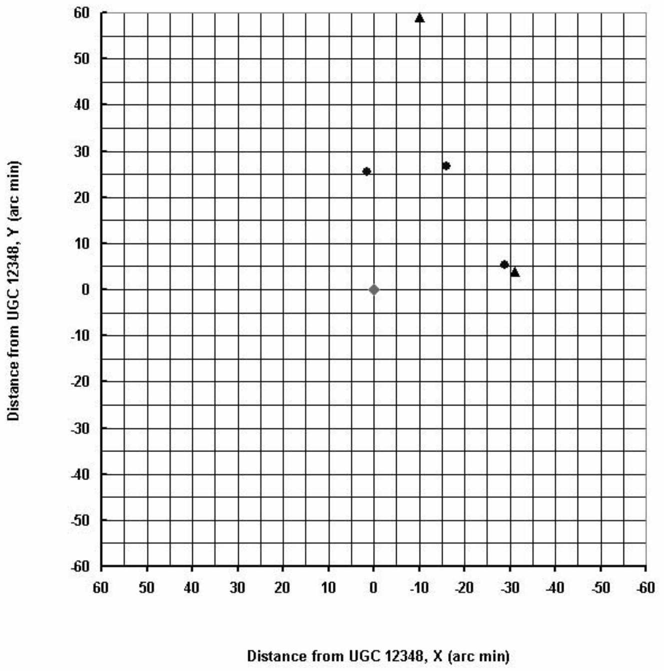

FIG. 1.—Distribution of GRBs and QSOs near UGC 12348. Circles show QSOs and triangles show GRB positions.

galaxy redshift. The average value of $|\, cz_{\rm D} \,|$ for this set is 12,400 km s^{-1} (Burbidge & Napier 2001). Thus, while the largest value here is above the mean, it is not unreasonably high.

3.4. *Bright Active Galaxies near GRBs in Table 1*

The majority of the objects listed in Table 1 lying within 1° of burst positions are faint high-redshift QSOs. However, there are also a number of much brighter AGNs with very small cosmological redshifts that in nearly all cases we believe are genuine spiral galaxies with active nuclei. In each case, if it could be demonstrated that the galaxy and the nearby GRB are physically associated, we would conclude that the active galaxy has ejected the GRB source. Six of these galaxies have been classified as Seyfert galaxies. We discuss them in turn:

NGC 3147.—This galaxy has been classified as Seyfert 2 and is known to be a strong X-ray source (Moran, Halpern, & Helfand 1996). Again, this is just the type of galaxy that was shown in the *ROSAT* survey to have X-ray–emitting QSOs clustered around it. At a cosmological redshift of 0.0096, its distance is 48 Mpc, and the projected separation of GRB and galaxy is 1.6 Mpc.

UGC 9944.—This galaxy has also been classified as Seyfert 2, by de Grijp et al. (1992). At a redshift $z_c = 0.025$, the projected separation of GRB and galaxy is 0.9 Mpc.

NGC 6500.—This is a marginal Seyfert galaxy (Seyfert 3) with a companion (Véron-Cetty & Véron 1986; Keel 1996). At a redshift $z_c = 0.01$, the projected separation of GRB and galaxy is 1.3 Mpc.

Padova 1.—This is a highly obscured Seyfert 1 galaxy (Sabbadin et al. 1989). With $z_c = 0.0088$, the projected separation between GRB and galaxy is 350 kpc.

UGC 12282.—This galaxy has been classified as Seyfert 1.9. It was discovered as an AGN because it is a strong *ROSAT* X-ray source (Bischoff et al. 1999). With a redshift of 0.017, the projected separation of GRB 010921 and the galaxy is 0.8 Mpc. The redshift of GRB 010921 is $z = 0.45$.

UGC 12348.—This galaxy and GRBs 991217 and 000519 were discussed in § 3.4. The galaxy was also classified as a Seyfert 2 (de Grijp et al. 1992). Since the redshift of the galaxy $z = 0.03$, the projected separations between the galaxy and the two GRBs are 1.4 and 2.6 Mpc, respectively.

Mrk 1400.—This has been classified as a Seyfert 1 galaxy. It was discovered in the Markarian surveys and has been observed and classified by Osterbrock & Dahari (1983). With a redshift $z = 0.029$, the projected separation between it and GRB 000911 is 1.4 Mpc.

ESO 184-G82.—This is the spiral galaxy that is associated with GRB 980425. Within the position of the error box of the burst, an unusual supernova, SN 1998bw, was detected at about the same time as the burst. This burst has been seen as an anomaly when compared with all of the other bursts that have been identified, because it apparently occurred in a comparatively nearby galaxy. However, the picture that we are developing here suggests that the true distances of the identified bursts are much smaller than those normally assumed. Thus, it may not be an anomaly. It has also been reported that within the error box of this burst, and hence very close to the center of the galaxy, there is a steady compact X-ray source (SAX J1935.0$-$5248) with a flux of 2×10^{-12} ergs cm^{-2} (2–10 keV; Galama et al. 1998). Assuming a distance of 42 Mpc, this source has a luminosity $L_{\rm X} = 4 \times 10^{41}$ ergs s^{-1}. This is comparable to the X-ray sources that lie near the centers of active galaxies such as M82. This suggests that perhaps ESO 184-G82 is also an active galaxy.

The observed properties of all these galaxies suggest that they are all active spirals, so that they may be the parent galaxies of the GRBs. However, the sample is small, and the angular separations are much larger than those for the QSO-GRB pairs discussed in § 3.1. Against this, it must be remembered that active spirals of this type comprise $\lesssim 10^{-2}$ of the total spiral population, and with the measured separations, rough statistical estimates based on equation (3) do not support the view that they are all physically associated. However, in two cases, UGC 12348, in which two GRBs and three QSOs with intrinsic redshifts are found (§ 3.3), and ESO 184-G82, in which the GRB occurs extremely close to the center of the galaxy, the evidence for physical associations is much stronger.

4. THE REDSHIFT DISTRIBUTION OF GRBs AND ASSOCIATED QSOs

In Table 3 we give a list of all the GRBs for which redshifts have been determined, together with the redshifts of the QSOs that have been shown to be associated with GRBs in § 3.1. The redshifts are listed in increasing order.

Apart from GRB 980425, which is associated with the nearby galaxy ESO 184-G82, there are 32 redshifts of sources or of QSOs very close to them. It is clear that there are two very close to $z_i = 0.30$ (mean $z = 0.32$), three close to $z_i = 0.60$ (mean $z = 0.70$), nine close to $z_i = 0.96$ (mean $z = 1.031$), three close to $z_i = 1.41$ (mean $z = 1.373$), six close to 1.96 (mean $z = 2.032$), two close to $z_i = 3.44$ (mean $z = 3.56$), and one very close to $z = 4.45$ ($z = 4.50$). Thus, 26 out of the 32 redshifts lie close to the intrinsic redshift peaks, and of these, 21 have $z > z_i$ and only five have $z < z_i$. This is further evidence in favor of the hypothesis that the

TABLE 3

Redshifts of Burst Sources and Afterglows and Nearby QSOs

Burst	z (Burst)	z (Companion Galaxy or QSO)
980425	. . .	0.0085 (ESO 184-G82)
990506	. . .	0.273
0.11121	0.36	. . .
990512	0.433	. . .
010921	0.45	. . .
970228	0.695	. . .
020405	0.695	. . .
991208	0.706	. . .
970508	0.843	. . .
990705	0.86	. . .
970828	0.958	. . .
980703	0.966	. . .
020531	1.00	. . .
991216	1.02	. . .
020127	. . .	1.025
940720	. . .	1.038
000911	1.059	. . .
980613	1.096	. . .
000418	1.119	. . .
990506	1.3	. . .
990625	. . .	1.344
010222	1.476	. . .
990123	1.600	. . .
990510	1.619	. . .
000210	. . .	2.02
001105	. . .	2.03
001105	. . .	2.03
000310	2.034	. . .
000926	2.037	. . .
001105	. . .	2.04
971214	3.418	. . .
991217	. . .	3.7
000131	4.50	. . .

galaxies of all these objects are farther away than the parent galaxies of the earlier samples of QSOs in which the original redshift peaks were found (e.g., Karlsson 1990; Burbidge & Napier 2001). For all of those QSOs, $z_c \leq 0.01$. Since we do not know what the values of z_c or $z_{\rm D}$ are for any of the bursts, but only that (for a different sample) $|\bar{z}_{\rm D}| \simeq 0.04$, we can only guess that for most of these sources, the parent galaxies have cosmological redshifts in the range 0.01–0.05.

Of course, there are six of the bursts that have measured redshifts that lie quite far from the intrinsic peak values. How are they to be interpreted? The most likely possibility is that they arise from galaxies that have larger cosmological redshifts. For example, if we assume for all of these that $z_c = 0.1$, we find that the values of $(z_i + z_{\rm D})$ lie very close to the previously determined values of z_i. For

$$\text{GRB 990512} \quad z_o = 0.433, \quad (z_i + z_{\rm D}) = 0.30\ ,$$
$$\text{GRB 010921} \quad z_o = 0.45, \quad (z_i + z_{\rm D}) = 0.32\ ,$$
$$\text{GRB 970508} \quad z_o = 0.835, \quad (z_i + z_{\rm D}) = 0.67\ ,$$
$$\text{GRB 990705} \quad z_o = 0.86, \quad (z_i + z_{\rm D}) = 0.69\ ,$$
$$\text{GRB 990123} \quad z_o = 1.600, \quad (z_i + z_{\rm D}) = 1.36\ ,$$
$$\text{GRB 990510} \quad z_o = 1.619, \quad (z_i + z_{\rm D}) = 1.38\ .$$

W. Napier has been kind enough to carry out a power spectrum analysis for the 33 redshifts in Table 3 using the same methods used in the previous studies of peaks and periodicities in the redshift distributions (Burbidge & Napier 2001). The result is shown in Figure 2.

There is a clear peak, of power $I \sim 9.3$ at $P = 8.57$ in units of $100 \log_{10}(1 + z)$. This can be compared with a "best estimate" of the periodicity from the QSO data obtained from the combined data sets of Karlsson (1990) and Burbidge & Napier (2001): the 283 QSOs of this combined data set (KBN) yield a strong peak ($I \sim 33.6$) at $P = 8.85$. A bootstrap analysis further yields $P = 8.85 \pm 0.28$ (90% confidence region) for the KBN data. That is, the best-fit periodicity of the γ-ray data lies just within the 90% confidence region of the periodicity found in the KBN data. We can then ask: How often would this circumstance arise by chance? That is, how often would data, random but with the overall distribution of the observed data set (Fig. 2), yield a best-fit periodicity within the 90% confidence region of the KBN, with strength $I \sim 9.3$?

To test this, Napier constructed data sets by sampling with replenishment from the redshifts of Table 3 and adding

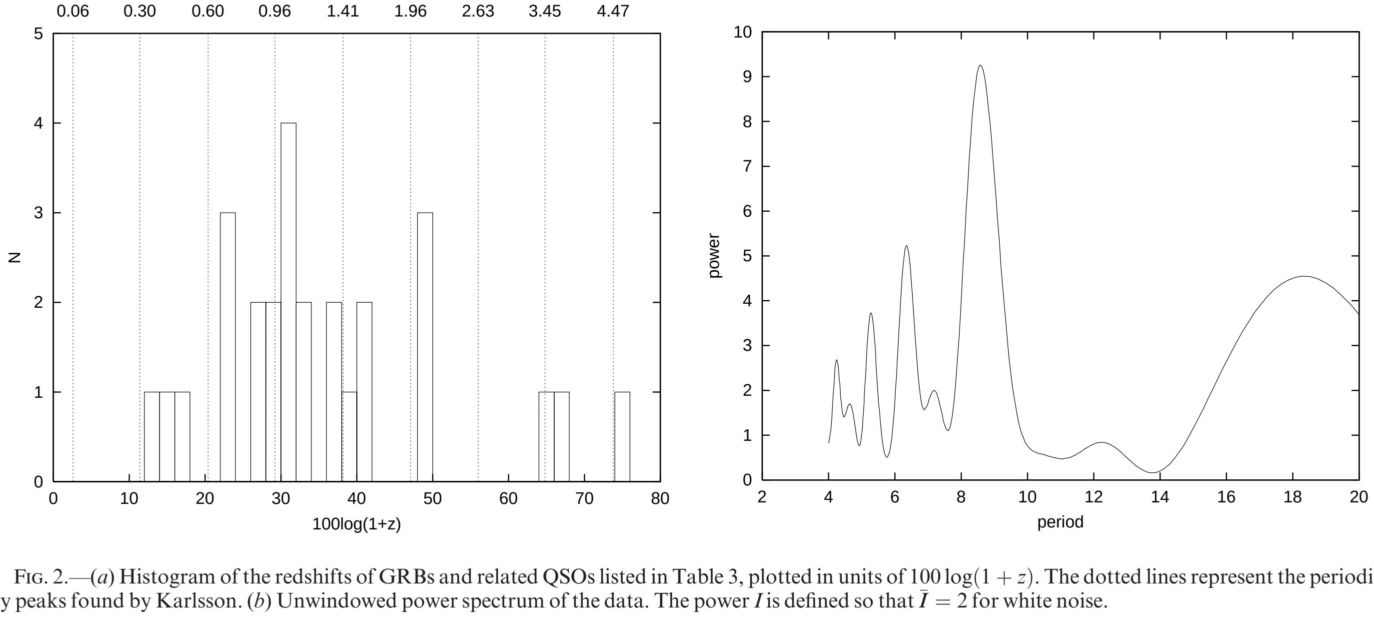

Fig. 2.—(*a*) Histogram of the redshifts of GRBs and related QSOs listed in Table 3, plotted in units of $100 \log(1 + z)$. The dotted lines represent the periodicity peaks found by Karlsson. (*b*) Unwindowed power spectrum of the data. The power I is defined so that $\bar{I} = 2$ for white noise.

random " noise " to each selected datum, sufficient to smear out the periodicity under test but not enough to change the overall redshift distribution. Each synthetic data set so constructed was analyzed in identical fashion to the real γ-ray data set of Table 3, and the best-fit periodicity and its strength were recorded in each case. It was found that out of 10,000 trials, 239 data sets yielded signals within the prescribed confidence region, and with strength $I \sim 9.3$; that is, the KBN periodicity is present in the γ-ray data at a confidence level of ~98%.

However, the derived phase of the γ-ray periodicity $\phi \sim 5.69$, which is just outside the 90% confidence region of the KBN phase: ϕ is outside the range of the original hypothesis.

The original hypothesis could be refined post hoc to get a better fit, but the proper procedure is to wait until sufficient fresh data have come along to prove or disprove the modified hypothesis. I have not chosen to do this because I have concluded that over nearly 3 years, the number of redshifts has increased fourfold, and the data appear to be trending in the right direction.

5. CONCLUSIONS

In this paper I have put forward a new hypothesis. This is that γ-ray burst sources are closely related to QSOs, which in turn are ejected from active galaxies. The evidence in favor of this rests on several kinds of observational evidence:

1. While only a comparatively small number of GRBs have been accurately located and only a very small fraction of the sky has been surveyed for QSOs, there are a number of very close pairings between QSO and burst positions.
2. The numerical values of the observed redshifts of many of the γ-ray sources or afterglows, or of QSOs that lie very near to the burst positions, are very close to peaks in the redshift distribution of QSOs, which other samples have shown must be largely intrinsic in origin. The majority of these observed redshifts are slightly greater than the intrinsic peak values, and this supports the view that they are ejected from active galaxies with cosmological redshifts in the range ~0.01–0.05.
3. One active galaxy, UGC 12348, which has a cosmological redshift $z = 0.03$, has two bursts GRB 991217 and 000519 lying within 1° of it and three QSOs that lie even closer. They each have a redshift that is very close to but greater than an intrinsic peak redshift.

The referee has pointed out that a number of the GRB positions overlap with the NRAO VLA Sky Survey or Faint Images of the Radio Sky at Twenty cm radio continuum survey, and thus an attempt could be made to look for further identifications by comparing with those survey objects. I agree that work along these lines could be attempted, but the problem is that most of these latter radio sources have not been identified with optical objects whose optical spectra have been obtained, and until this is done, we would not know whether the source is a QSO, a radio galaxy, or a comparatively normal but very faint galaxy. What are clearly needed are detailed optical studies with spectroscopy of all of the objects seen in the error boxes of the GRBs. So far, the concentration has been on objects lying within a few arcseconds of the burst position. If the hypothesis proposed here is correct, QSOs and active galaxies up to $10'$–$20'$ from these positions should be found, as they are, for example, in the position of GRB 001105.

The referee has also raised the point that while I have quoted the paper of Bloom et al. (2002) as evidence for cosmological redshifts, the conclusions of this investigation suggest that the bulk of the redshifts of GRBs are noncosmological in nature. This is indeed a dilemma. It can be resolved either by concluding that there are two classes of GRBs or by concluding that one of the hypotheses is wrong. My own belief is this, that the true nature of what are generally called starburst galaxies is still to be sorted out. In addition, the absorption redshifts that have been used to determine distances for many GRBs have been misinterpreted. If the QSOs have small values of z_c, large values of $z_{\rm abs}$ must have an intrinsic origin, i.e., they must be associated with gas ejected from the QSOs and not gas in the intervening space.

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