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A Search of the Northern Sky for Ultra High Energy Point Sources

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Abstract

A search has been made for steady emission of ultra high energy radiation from individual point sources over most of the northern sky. Over 200 million air showers induced by primary particles of energy greater than about 10 TeV were recorded from 1986 April until 1991 May by the CYGNUS air shower array. No statistically significant excess above the background from the isotropic flux of cosmic rays was found for any direction in the sky from 0° to 80° declination. In addition, 49 specific potential sources were examined and none showed a statistically significant excess of events. 90% confidence level flux upper limits are established for the continuous emission from these sources; for a source that transits the zenith, a representative upper limit corresponds to an integral flux above 40 TeV of about 1.7×10^{-13} cm^{-2} s^{-1} (0.5% of the cosmic ray flux within an angular area of 1.8×10^{-3} sr) assuming a power law energy spectrum with a differential spectral index of -2.7.

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There is great interest in point sources of very energetic (above about 1 TeV) γ-rays. Aside from the possibility of increasing what is known about sources of x-rays and lower energy γ-rays, it may be that compact astrophysical systems are capable of producing most or all of the high energy cosmic rays. If a steady point source of very energetic γ-raysis found, it may provide a good source of high-energy particles for the study of particle interactions in the atmosphere.

Although there have been detections reported of either steady, pulsed, or episodic emission at energies above about 1 TeV from many different sources (Fegan 1990), only two have been observed as constant sources by at least two independent observations: Cygnus X-3 by Samorski & Stamm (1983) and by Lloyd-Evans *et al.* (1983) and the Crab by Vacanti *et al.* (1991) and by Akerlof *et al.* (1989). Moreover, Cygnus X-3 is apparently no longer a source at these energies (Dingus *et al.* 1988; Alexandreas *et al.* 1990). Nevertheless, because cosmic ray particle acceleration to energies above 10's of TeV is not well understood (Harding 1990), it is important to know which astrophysical objects are potential sources at these energies; thus, the need to search for emission from a variety of previously identified lower energy sources and from undiscovered sources, i.e. an "all-sky" survey.

The CYGNUS air shower experiment operates nearly continuously and has collected about 210 million ultra high energy (UHE) air shower events during the time period between 1986 April and 1991 May. While the experiment has been described in detail elsewhere (Alexandreas *et al.* 1991a; Allen *et al.* 1991), the most important features will be outlined here. The experiment is located at an altitude of 7000' (overburden of 800 g/cm^2) in Los Alamos, NM (106.3° W, 35.6° N), so the entire northern sky passes overhead each day.

The experiment began operation with 50 scintillation counters, each about 1 m^2 area, deployed over an area of about 10,000 m^2 and operating at a trigger rate of about 0.5 sec^{-1}. Since that time, the experiment has undergone several expansions and now consists of 204 lead-covered counters deployed with a graded spacing over a total area of about 85,000 m^2 with an air shower trigger rate of about 5 sec^{-1}.

The average angular resolution of the array, determined by observations of cosmic ray shadowing by the sun and moon, is 0.75°(Alexandreas *et al.* 1991b; Alexandreas *et al.* 1991c). According to simulations, the acceptance

of the array begins for primary energies of about 10 TeV while the most probable energy of a detected cosmic ray is about 40 TeV corresponding to a shower size of about 10^4 particles. The combination of large area, low threshold, and good angular resolution make the experiment well suited for searching for point sources of radiation at these energies.

For each candidate point source position, the analysis must be able to predict the expected number of air shower events assuming there is no source (the expected background from cosmic rays); this can then be compared with the observed number of events to determine if there is an excess due to a source at that position. There are many effects in an air shower experiment that, if not handled properly, could cause possible large systematic errors that could either hide a real point source or apparently create one where none actually exists. These effects include: times when the experiment was not operating, short and long term event rate variations due to local air pressure changes and detector upgrades, respectively, and to non-uniformities in the acceptance of the array to air showers, which depends on, for example, the precise way the scintillators are deployed. These effects can cause variations in the effective exposure of the array to different parts of the sky.

A technique has been developed that is able to estimate the number of expected background events at each point in the celestial sky, even though each of the above effects exists in the data, without having to make any cuts on the data. First, the number of observed events at each position in the sky is determined by accumulating the events in 0.2° bins in both right ascension (α) and declination (δ). Then, the background must be estimated from the data.

The method of background determination uses the data recorded by the experiment to measure, in local coordinates (zenith θ, azimuth ϕ, and time), the current sensitivity of the array. This is accomplished by accumulating the zenith and azimuthal angle distribution of a large number of events, $N(\theta, \phi)$. A sample of 20,000 events is used for this distribution (20,000 events are accumulated in about 12 hours during the early running period and in 1 hour during the most recent running). For each observed event, a random "background" event is created by using the event time and choosing new local coordinates randomly from $N(\theta, \phi)$; the celestial coordinates for the "background" event are then determined and binned

in the same way as for the observed data. This procedure is repeated 10 times for each observed event so that the statistical uncertainty in the background estimate is relatively small. During the data processing, a new $N(\theta, \phi)$ distribution is accumulated to be used for the next set of events, thus allowing for variations in this distribution over rather short timescales. Further, because randomized events are generated using the actual event times, the method correctly accounts for periods when the experiment was not operating, as well accounting for changes in the trigger rate. Several checks have been made of the results, and no systematic errors were found; the checks include a comparison of these results with those of two different analyses of events from the Crab region, and verifying that the apparent fluctuations about the expected background are as expected by statistics.

In searching for a continuous signal from a point source a bin of radius about 1.2° should yield the optimal statistical significance for the resolution of the CYGNUS array. For this analysis, a corresponding square bin is used with dimensions 2.4° in δ and $2.4°/\cos(\delta)$ in α, rounded to the nearest 0.2°in α, centered on the potential source location. For the all sky survey, the northern sky between 0° δ and 80° δ was divided into a non-overlapping grid of about 3,600 independent bins and the excess in each bin above the expected background was calculated. The distribution of the excess events in each bin is shown in Figure 1. Since a potential point source may lie near the boundary of one of these bins, three other similar binnings of the sky are made by moving the bin boundaries by 1/2 of a bin in α, by 1/2 of a bin in δ, and by 1/2 of a bin in both α and δ. There is no statistically significant excess of events above background for any of the bins.

An upper limit on the flux has been calculated for each of these points. The method for determining the upper limit to the flux will be outlined here. For a given source position, an upper limit on the excess number of events above the observed cosmic ray background (above the minimum detectable energy (E_0)) is determined, N_{lim} (Aguilar-Benitez *et al.* 1986); 90% confidence level limits are chosen and include the uncertainty in the estimation of the background. The limit on the integral flux is then

$$F(> E_0) < \frac{N_{lim}}{N_{cr}} \frac{1}{R(\gamma)\epsilon} F_{cr}(> E_0)\Delta\Omega$$

where N_{cr} are the number of cosmic ray events in the bin, $R(\gamma)$ represents

the sensitivity of the array to photons of spectral index γ relative to cosmic rays (R = 1.4 for γ = -2.7 and 5.0 for γ = -2.0), ϵ represents the loss of events outside of the bin (72% should fall inside the source bin), F_{cr} is the cosmic ray flux above 10 TeV (2×10^{-7} $cm^{-2}s^{-1}sr^{-1}$), and $\delta\Omega$ is the solid angle subtended by the source bin (1.8×10^{-3} sr). Although the minimum detectable energy for the CYGNUS array is about 10 TeV, the flux limits are given at the energy that corresponds to the peak of the observed cosmic ray spectrum, 40 TeV, by extrapolating from 10 TeV to 40 TeV according to the assumed spectral index γ = -2.7; it should be remembered that the array has considerable sensitivity below 40 TeV with about 30% of the cosmic ray events occurring below this energy. Figure 2 illustrates the upper limits on the continuous flux above 40 TeV that would correspond to zero excess events for a bin, as a function of the δ of the bin.

In addition to the all sky survey, 49 potential point sources have been examined using the same method except that the bins are centered on the candidate source. The candidate source list includes previously reported very-high energy and ultra high energy sources, selected pulsars, cataclysmic variables, galaxies, and selected x-ray and γ-ray sources. No source shows a significant excess above expectation; Table 1 presents the results and flux upper limits. Some of these limits appear to be in disagreement with previously reported observations by other groups (Muraki *et al.* 1991; Tonwar *et al.* 1988).

Using a data set of over 200 million air shower events collected between 1986 April and 1991 May by the CYGNUS air shower array, an "all-sky" search for point sources of radiation was made with no evidence found for a steady source of UHE radiation. Upper limits at the 90% confidence level on the continuous flux above 40 TeV from a source that transits the zenith are about 1.7×10^{-13} cm^{-2} s^{-1} (0.5% of the cosmic ray flux). These limits imply that a detection of one of these sources at a significance of at least 5σ by this or a similar array will require a data set at least 10 times larger than the present one. While it would be very desirable if one or more continuous sources of UHE radiation existed so that it could be used to study particle interactions in the atmosphere and as a "standard candle" for the field, it is perhaps likely that point sources of UHE radiation emit only sporadically. Of course, these limits do not preclude the possibility of a large flux for a short time (Alexandreas *et al.* 1991d), as would be expected from a sporadic

source, nor of a fairly large pulsed flux, as long as the duty cycle is short enough to keep the time-averaged flux below the limits.

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Table 1. The limits from 49 potential point sources. N_{on} and N_{off} are the number of events observed from the source position and the number expected from the cosmic ray background, N_{σ} is the number of standard deviations excess above the background, F_{lim} is the 90% confidence level upper limit on the fractional excess above the background, and the flux limit, F_0 is assuming a differential power law spectral index of -2.7.

Source	α (°)	δ (°)	N_{on}	N_{off}	N_σ	F_{lim} (% of CRs)	$F_0(>40TeV)$ ($\times 10^{-13}$ cm^{-2}s^{-1})
Cyg X-3	307.7	40.8	94869	94859	0.0	0.57	1.9
Her X-1	254.0	35.4	95774	95956	-0.6	0.47	1.6
Crab	82.9	22.0	64792	64325	1.8	1.28	4.4
Cyg X-1	299.1	35.1	96308	96441	-0.4	0.48	1.6
M31	9.9	41.0	85459	85417	0.1	0.63	2.2
Virgo A	186.9	12.7	43114	42801	1.5	1.42	4.8
AM Her	273.7	49.8	86184	86688	-1.7	0.34	1.2
DQ Her	271.6	45.9	89747	90228	-1.6	0.35	1.2
U Gem	118.0	22.1	65949	66038	-0.4	0.60	2.1
SS Cygni	325.2	43.4	92466	92574	-0.4	0.51	1.7
HZ 43	198.5	29.4	85641	86178	-1.8	0.34	1.0
GK Per	52.0	43.7	84677	84351	1.1	0.90	3.0
V404 Cygni	300.4	33.8	90209	90134	0.2	0.63	2.1
Kiel 1	36.0	32.3	79894	79721	0.6	0.76	2.6
Kiel 3	270.3	42.6	93139	92784	1.2	0.85	2.0
Kiel 4	36.2	61.1	48834	49238	-1.8	0.45	1.5
Kiel 5	352.7	67.4	33514	33490	0.1	1.01	3.4
Kiel 6	3.4	25.9	71023	70593	1.6	1.15	3.9
Geminga	97.4	17.8	56673	56339	1.4	1.20	4.1
1E2259+58	344.8	58.6	57499	57718	-0.9	0.54	1.8
SS433	287.3	4.9	25457	25413	0.3	1.22	4.1

4U0042+32	10.5	32.8	80887	80683	0.7	0.79	2.7
4U0115+63	18.8	63.5	43296	43051	1.2	1.28	4.3
4U0316+41	49.1	41.4	83756	83821	-0.2	0.55	1.9
4U0352+30	58.1	30.9	79612	79366	0.9	0.85	2.9
4U0614+09	93.6	9.2	32400	32273	0.7	1.25	4.3
4U1257+28	194.4	28.2	84892	84702	0.6	0.76	2.6
4U1651+39	252.9	39.9	97619	97268	1.1	0.83	2.8
4U1837+04	279.4	5.0	25899	25831	0.4	1.28	4.3
4U1901+03	285.4	3.1	21316	21449	-0.9	0.89	3.0
4U1907+09	286.8	9.7	37507	37180	1.7	1.61	5.4
4U1918+15	289.7	15.0	50851	51124	-1.2	0.51	1.7
4U1957+40	299.3	40.5	96725	96333	1.3	0.87	3.0
4U1954+31	298.5	32.0	90049	90213	-0.6	0.48	1.6
4U2142+38	325.6	38.1	91096	90358	2.4	1.28	4.4
4U2321+58	350.3	58.6	56988	57102	-0.5	0.63	2.1
2CG075+00	304.8	36.4	94480	95241	-2.5	0.26	0.9
2CG078+00	305.4	39.8	96970	96795	0.6	0.69	2.3
2CG095+04	318.8	55.0	66708	67201	-1.9	0.37	1.2
2CG135+01	38.2	61.7	46680	46803	-0.6	0.67	2.3
2CG121+04	7.2	66.5	35720	35635	0.4	1.09	3.7
PSR0355+54	58.8	54.1	65304	64833	1.8	1.28	4.3
PSR0950+08	147.6	8.2	30874	31114	-1.4	0.62	2.1
PSR1929+10	292.5	10.9	40173	40301	-0.6	0.70	2.4
PSR1937+21	294.4	21.5	71285	71167	0.4	0.77	2.6
PSR1951+32	297.8	32.7	89889	90377	-1.6	0.35	1.2
PSR1953+29	298.2	29.2	88426	88620	-0.6	0.47	1.6
PSR1957+20	299.4	20.7	69072	69234	-0.6	0.53	1.8

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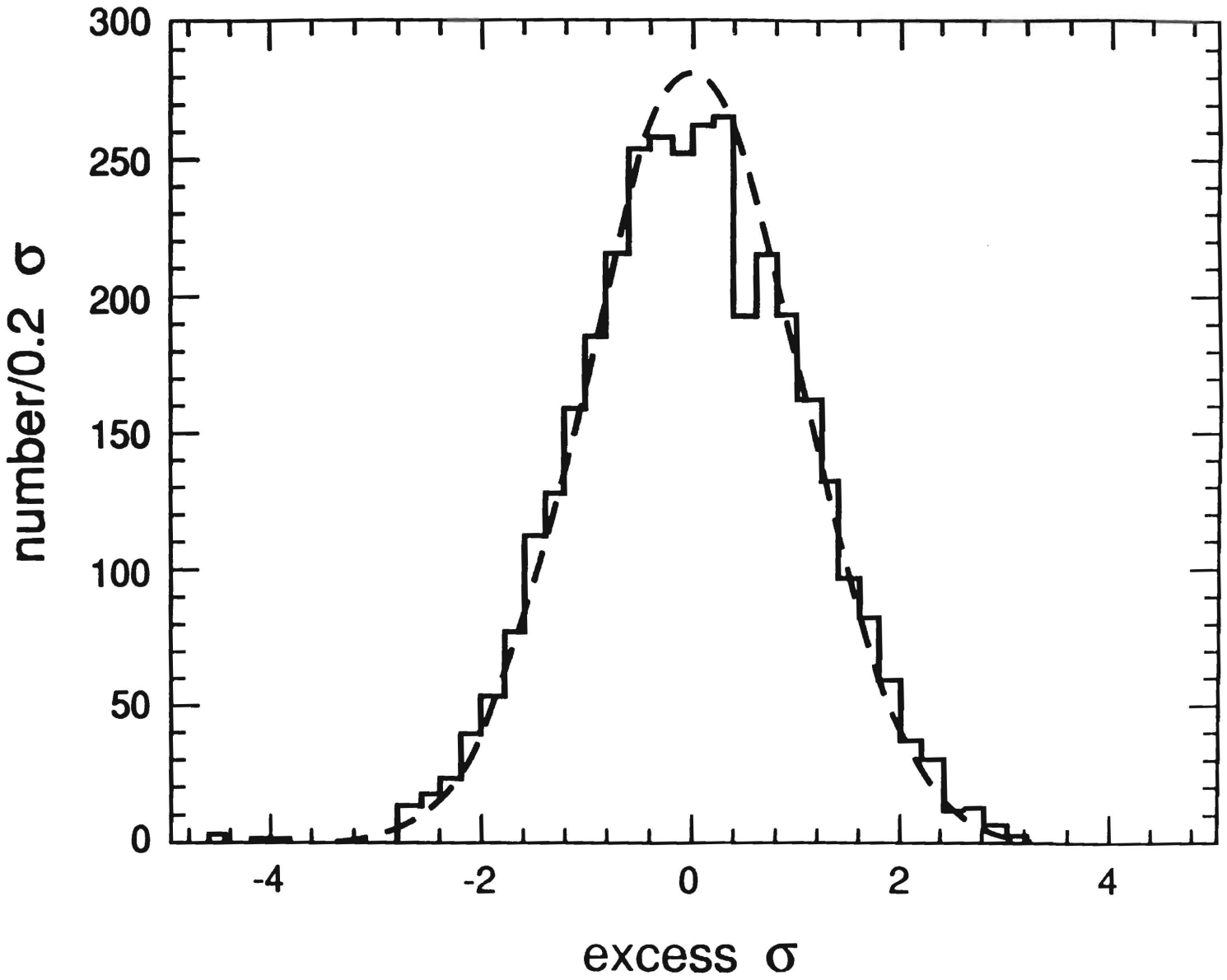
Figure Captions

Figure 1. The distribution of the excess number of events above the cosmic ray background from each of 3,600 non-overlapping bins. The dashed curve is a Gaussian distribution expected from only fluctuations of the background; the Gaussian fits the data well with a χ^2 of 50.8 for 49 DoF.

Figure 2. The 90% confidence level flux upper limit from a candidate point source as a function of declination assuming there is no excess events observed from the source position. The flux limits assume a power law spectrum with a differential spectral index of -2.7; the limits would be about 25% lower for a spectral index of -2.0.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number/0.2 σ
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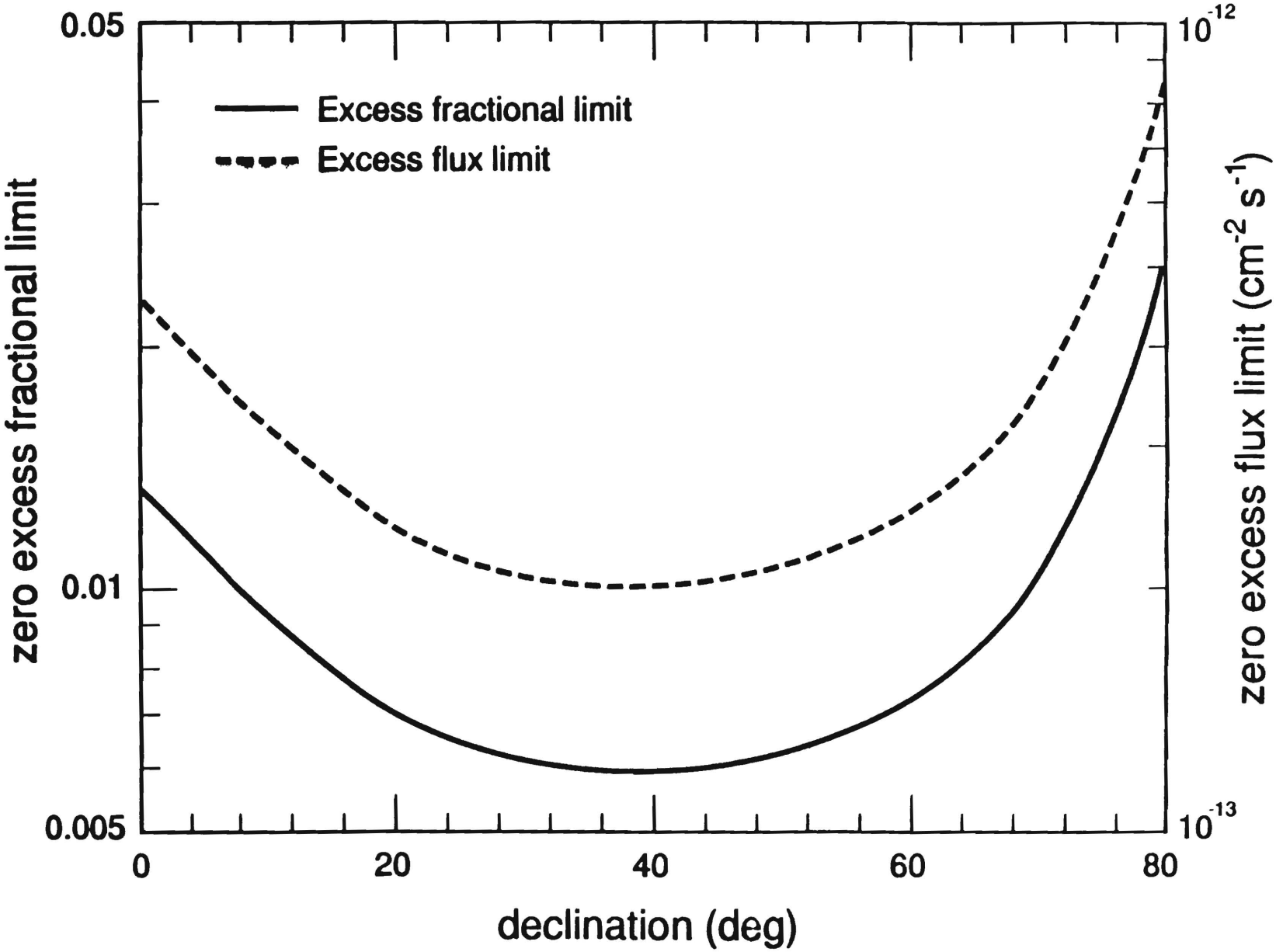
Excess fractional limit
Excess flux limit
zero excess fractional limit
zero excess flux limit (cm^{-2} s^{-1})
declination (deg)
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0.01
0.005
10^{-12}
10^{-13}
0
20
40
60
80