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Abstract

The gamma-ray burst of 28 January 1976, one of 18 events thus far detected in interplanetary space with Helios-2, was also observed with the Vela-5A, -6A and the Ariel-5 satellites. A small source field is obtained from the intersection of the region derived from the observed time delays between Helios-2 and Vela-5A and -6A with the source region independently found with the Ariel-5 x-ray detector. This area contains neither any steady x-ray source as scanned by HEAO-A nor any previously catalogued x-ray, radio or infrared sources, x-ray transients, quasars, seyferts, globular clusters, flare stars, pulsars, white dwarfs or high energy gamma-ray sources. The region is, however, within the source field of a gamma-ray transient observed in 1974 (A. Jacobson et al., 1978), which exhibited nuclear gamma-ray line structure.

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Introduction

The sources of gamma-ray bursts have remained a mystery since their discovery over five years ago. The Helios-2 spacecraft, in solar orbit at distances of up to 2 AU from the Earth since January, 1976, carries the first instrument operating in space designed specifically to study cosmic gamma ray bursts. It is also the first burst detector put into interplanetary space for the purpose of obtaining high-resolution burst source locations by use of its long baseline for time-of-flight source triangulation. Wave front timing from Earth-orbiters to Helios-2 can provide source fields $\leqslant$ one arc-minute by several degrees in extent; triangulation with Helios-2, Earth-orbiters and the Venus probes launched in 1978 will soon provide source fields $\leqslant$ one square arc minute in size.

The 28 January 1976 gamma-ray burst, the first confirmed Helios-2 event, was also observed with the X-ray sky survey instrument on the Ariel-5 satellite, as well as with Vela-5A and -6A. This fortuitous circumstance has made possible a significant reduction in the size of the triangulated burst source region, and in fact gives the smallest burst source field yet obtained, about one square degree in size. The source region derived contains no known x-ray emitters or other "interesting" known galactic or distant objects. This result severely restricts the applicability of many source models. Both this region and the well-known high-energy gamma-ray source γ 195+5 are inside the source field of a gamma-ray flare, observed with a high-resolution gamma-ray spectrometer in 1974 (A. Jacobson et al., 1978), which exhibited nuclear gamma-ray line structure. The gamma-ray line flare may be entirely unrelated to either of the other phenomena, but these circumstantial associations suggest that the studies of gamma-ray transients and of line spectroscopy in gamma-ray astronomy may provide some of the most valuable new insights in high energy astrophysics.

Instrumentation

At the time of the discovery of gamma-ray bursts (Klebesadel et al., 1973), it was apparent that the opportunities were limited for obtaining high-resolution source positions by the triangulation technique using interplanetary space probes. By providing very long base lines these are capable of great directional accuracy, but most employ on-board power sources which generate intense gamma-ray background fluxes. The payload then under construction for the solar orbiter Helios-2 provided the first available benign platform, and was accordingly modified to contain a small piggy-back instrument adequate for the detection of bursts of the known intensity, energy spectrum, and frequency of occurrence. This package, added to the NASA/Goddard cosmic-ray detector, weighs 1.1 kg, requires 0.2 watt, and uses $\lesssim$ 25 kbits telemetry only when the memory is read out (averaging $\lesssim$ 0.02 bits per second). Launched on 15 January 1976, it is still fully operational. To date, it has detected at least 18 known bursts, missing 4 due to solar activity or to telemetry loss by solar transit.

The Helios-2 sensor is a 3.8-cm by 1.9-cm CsI crystal with a command-adjustable threshold set at $\approx$ 100 keV. Three command-adjustable trigger modes are used in order to accommodate the widely varying known intensity risetimes, set in flight at levels that are as sensitive as are commensurate with tolerable background rates. Following the occurrence of any trigger, both the immediately preceeding and the post-trigger time histories are stored in six memories on three nested time scales, so as to preserve precursor information and to obtain the fastest time structure nearest the trigger time. That time, to which the memories are locked, is also stored and is read out repeatedly for redundant determination. As a result, burst histories up to 2 minutes in duration are preserved with temporal accuracy as fine as 4 msec.

The spacecraft clock time of the trigger provides the critical element of the observation, since the comparison of the time delays between the spacecraft involved ultimately gives the source direction by wavefront triangulation. This time has been checked and verified using several independent means. The primary calibration uses artificial burst trigger commands, which have been telemetered to the vehicle on a number of occasions. Knowing the times of command transmission and the distances of the spacecraft, the spacecraft clock has been verified in all cases. The accuracy of agreement is, however, limited by knowledge of the command encoding and decoding delays to a time of the order of several hundred milliseconds. This inaccuracy is completely removed using the roll modulation of the burst intensity profiles. This effect results from the restricted solid angle of view of the burst sensor in its mounting position and is maximized for sources near the ecliptic (spin) plane of the spacecraft. The direction of the maximum intensity is independently measured in terms of its solar ecliptic longitude by the spacecraft optical aspect sensor. Any error in the timing of the burst profile that is greater than 60 milliseconds (modulo the 0.99-second spin period) would be evident in this comparison. Also, structures in solar x-ray flares have caused gamma-ray burst-like triggers, which, when compared with data from Earth-orbiters, have provided agreement with the Sun-Helios vs. Sun-Earth distances, limited to ≈ 1 light-second by the flare profile comparisons. Agreement in every case verifies that there are no detectable systematic timing errors. The greatest timing error is always the inaccuracy involved in the wavefront timing comparisons, necessary to correct for the different moments of triggering by various detectors within the burst temporal history. This depends on the counting rate statistics and the shape of the intensity profile and can vary widely. It amounts to several hundred milliseconds for the 28 January 76 event, due to the particularly slow nature of this gamma-ray burst.

The Vela-5A and -6A instruments that triggered on this event were two of the four which originally discovered the gamma-ray burst phenomenon (Klebesadel et al., 1973). The Vela-5A detector is the most sensitive and has an effective area a little larger than that of the Helios-2 detector; also, its energy threshold is about 150 keV, not far above the Helios-2 threshold. Consequently, the Vela-5A and Helios-2 time histories are statistically alike, as shown in Figure 1. The Vela-5A counting rates are accumulated on a geometrically expanding time scale, as is evident in the figure, while the Helios-2 rates illustrated have been converted to counts per 0.99-second satellite spin interval. Detailed comparisons of the time histories (using the 32-msec Helios-2 rates and taking the roll modulation into account), indicate a Helios-2 trigger delay, relative to Vela-5a, of 250 to 920 msec, with four probability maxima at 280 $\pm$30, 350 $\pm$30, 420 $\pm$30 and 800 $\pm$120 msec., with the most likely at 420 msec.

The Vela-6A sensor also triggered on this event, but, due to its much lower sensitivity, its time history following trigger was both poorly resolved and delayed, relative to the Vela-5A measurement. Consequently, the Vela-5A to -6A comparison has a resolution time about one-third their photon travel time separation. The crescent-shaped source region resulting from this analysis, however, contains the intersection of the Helios-2--Vela-5A and Ariel-5 source regions.

The Helios-2 intensity modulation, due to source obscuration by the satellite body during its spin, also provides two independent coordinates of the source position. The amplitude of the roll modulation in this event is as large as is seen, indicating that the source position is near the ecliptic plane, the satellite spin equator. This agrees with the final comparison with Ariel-5. The phase of the roll modulation provides the solar ecliptic longitude of the source from the satellite sun sensor. This position, illustrated in Figure 2a, also agrees with the final results of the Ariel-5 vs. Helios-2--Vela-5 source directional analysis.

The Ariel-5 sky survey instrument and its capabilities have been previously described (Villa et al., 1976; Cooke et al., 1978). Additional discussion is warranted here both since the gamma-ray event has a harder spectrum than the instrument was designed to study and since the source direction derived is slightly outside the field of view for x-rays in the lowest-energy design region. The instrument consists of a set of Argon-Zenon-CO_2 proportional counters, viewing from the side of the spin-stabilized spacecraft and having a fan beam field of view set by mechanical collimators. The soft x-ray field of view is 0.75° by 10.6° FWHM, with the long axis inclined at 65 degrees to the spin plane. As the satellite spins, data are accumulated into 1024 bins for up to one ≈ 1.5-hour orbit, so that each bin is populated by counts from a 0.35-degree wide fixed celestial position. In this operation mode no spectral resolution is obtained, so that for x-ray sources with a typical spectrum, the data represent counts in the $\approx$ 2-17 keV range.

The 28 January gamma ray burst was detected as a single-orbit transient (see Figure 2b). The derived source position was scanned from 6.41 to 6.65 and from 7.36 to 7.65 hours UT, containing the time of the event at 7.49 hours. The spin period of the satellite is 5.4 seconds, so that the > 40-second transient was seen in up to seven or eight spins, making a directional bias extremely unlikely. The counting rate history shown is adjacent to and readily compared with that of the source Mon X-1. Although the excursion is 5 sectors wide, a narrow peak is discernible with 1-sector resolution. It is fair to conclude that the scattering of the higher-energy transient photons did not produce a significant degradation of the directional resolution for this event.

The source region found here extends from near the high-elevation limit of the very low-energy x-ray f.o.v. to $\approx 2^{\circ}$ beyond it, but at a place where the efficiency is rapidly rising with energy, being 0.3% at 13 keV and 2% at 17 keV. The electronic upper threshold of the detection energy window is about 14.5 keV, but photons of higher energy will be detected with decreasing efficiency for up to several additional keV. In addition, energy degradation of higher energy photons will contribute to an extension of the apparent length of this viewing region. Using a 1.5% average efficiency, the 130-photon peak represents a flux of about 6×10^{-7} erg cm^{-2}. Taking into account the 5.4-second spin of the Ariel-5 satellite and assuming that the soft photon light curve was similar to the known > 100-keV portion, the total flux in the ≈ 10 to 17 keV range is estimated to be about 2×10^{-4} erg cm^{-2}. This is consistent with the IMP-7 measurements of this event (Cline and Desai, unpublished), assuming that the lower energy spectral shape is similar to, e.g., that of the Apollo-16 event (Metzger et al., 1974). This assumption is reasonable since the IMP-7 spectrum of this event, Figure 2c, has the same shape as that found to be typical for all known IMP-7 events (Cline and Desai, 1975) and as the Apollo-16 event in the same energy range.

Finally, the position error measured in orbit as a function of instrument elevation angle for known sources such as Tau X-1 shows no deviation for elevation angles up to 7 degrees, is less than ± 0.2 sector wide at 10 degrees, and gradually increases to ± 0.8 sector at 15 degrees. Thus, at the determined source elevation, there is almost no appreciable increase in the source location systematic error for sources such as Tau X-1. For this transient event, with its > 40-second duration and hard spectrum we conclude that the maximum width of the positional location is 1.5 sectors, or 0.5 degree.

<u>Results</u>

The source field derived is shown in Figure 3 as consisting of the four shaded regions within the diamond-shaped intersection. This source field does not include or intersect the source error boxes of any known x-ray emitters. It also does not include any "interesting" galactic candidate source objects such as known pulsars, white dwarfs, radio or IR objects or magnetic stars, nor does it contain known quasars or other anomalous distant objects. The position of the quasar 3C175 is marked on the figure as that with the least angular deviation. The γ-ray source

γ195+5 (Hermson et al., 1977; Kniffen et al., 1978) is also illustrated as the only x-ray or higher-energy γ-ray source in the nearby field. The most curious source association is that of a 20-minute gamma-ray transient on 10 June 1974, which exhibited line structure at 0.41, 1.79, 2.22 and 5.95 MeV (Jacobson et al., 1978). The instrument field of view for that observation is over 20^{o} wide, so that the association of the gamma-ray line transient with either the high-energy gamma-ray source γ195+5 or the 28 January 1976 gamma-ray burst may be entirely accidental.

A speculative neutron-star explanation for the slow line transient has been advanced (Lingenfelter et al., 1978) which accounts for both the apparent deuterium line and for redshifted annihilation, deuterium and iron lines. Whether this phenomenon is related to gamma-ray bursts remains to be seen, but the possibility exists: the total observing time for slow transients is the integrated time γ-ray spectrometers have been balloon-borne, i.e., a few tens of hours. The intensity of the 1974 transient is such that it cannot be seen by any existing satellite γ-ray burst instrumentation. Thus, one can conclude that slow transients might be found to occur as often as bursts, given appropriate observing programs. A common origin hypothesis, however, suffers from the fact that γ-ray bursts have not been shown to repeat from the same source, although there are some suggestions of this (Klebesadel and Strong 1976).

The γ-ray burst discussed here was the only one observed with Ariel-5 out of 15 known events in 1976 and 1977. However it was one of a similar number of moderate to high galactic latitude x-ray transients seen by Ariel-5 during the same time period (K. Pounds, unpublished). Thus, the probability also exists that a class of x-ray transients may be phenomenologically related to γ-ray bursts, even though, e.g., x-ray bursters appear to be a quite distinct phenomenon. These questions may be answered when the Helios-2 burst observing program combines with those of the other, more recently launched, interplanetary sensors on Pioneer-Venus, ISEE-C, and Venera-11 and -12 to provide high-accuracy γ-ray burst source fields.

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Figure Captions

Figure 1. Time histories of the intensity above background of the 28 January 1976 gamma-ray burst, as observed with Helios-2 and Vela-5A. The Helios-2 counting rates are shown converted to totals per 0.99-second spin period.

Figure 2. (a) The Helios-2 32-millisec intensity history superimposed to obtain a spin aspect count rate profile. The solar ecliptic longitude of the Ariel-5 source position is shown for comparison; it is in agreement with the expected median position of the observed peak intensity.

(b) The counting rate directional scan of Ariel-5 for orbit 7133. The known position of the x-ray source Mon X-1 fixes the calculated source position of the 28 Jan 76 burst.

(c) The photon spectrum of the 28 January 76 event measured with IMP-7 and the typical event-average relative spectrum of earlier IMP-7 gamma-ray bursts (Cline and Desai, 1975). This relative spectrum, common to all known bursts throughout the 0.15 to 1.2 MeV energy region, fits on to the lower-energy spectrum of an Apollo-16 event (Metzger et al., 1974), permitting a normalization to the low-energy Ariel-5 data.

Figure 3. The gamma-ray burst source region (1950.0 coordinates) found using the Ariel-5 source location and the Helios-2 to Vela-5A and -6A time delays. The 95-percent confidence region is the total area enclosing the four shaded regions

of maximum probability. No known x-ray sources are within or adjacent to this position. Scanned on two occasions by chance with the high--sensitivity NASA/ Goddard x-ray detector on HEAO-A, it was found to contain no visible intensity increases on 10 Oct. 77 or 7 Apr. 78 (F. Marshall and E. Boldt, pri. comm.). However, it is clearly well within the large source field of a 20-minute gamma-ray line transient observed on 10 June 1974 (Jacobson et al., 1978).

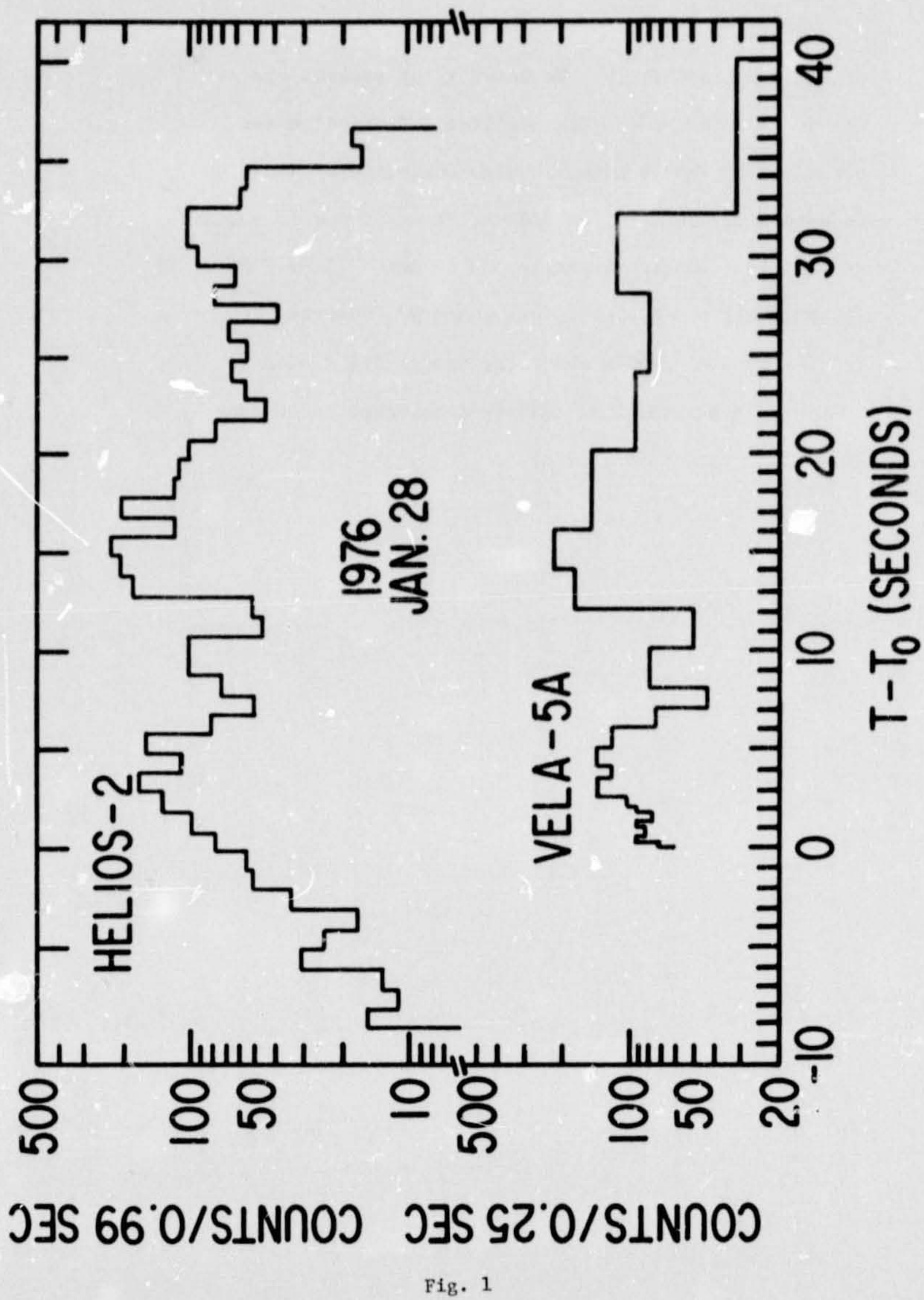
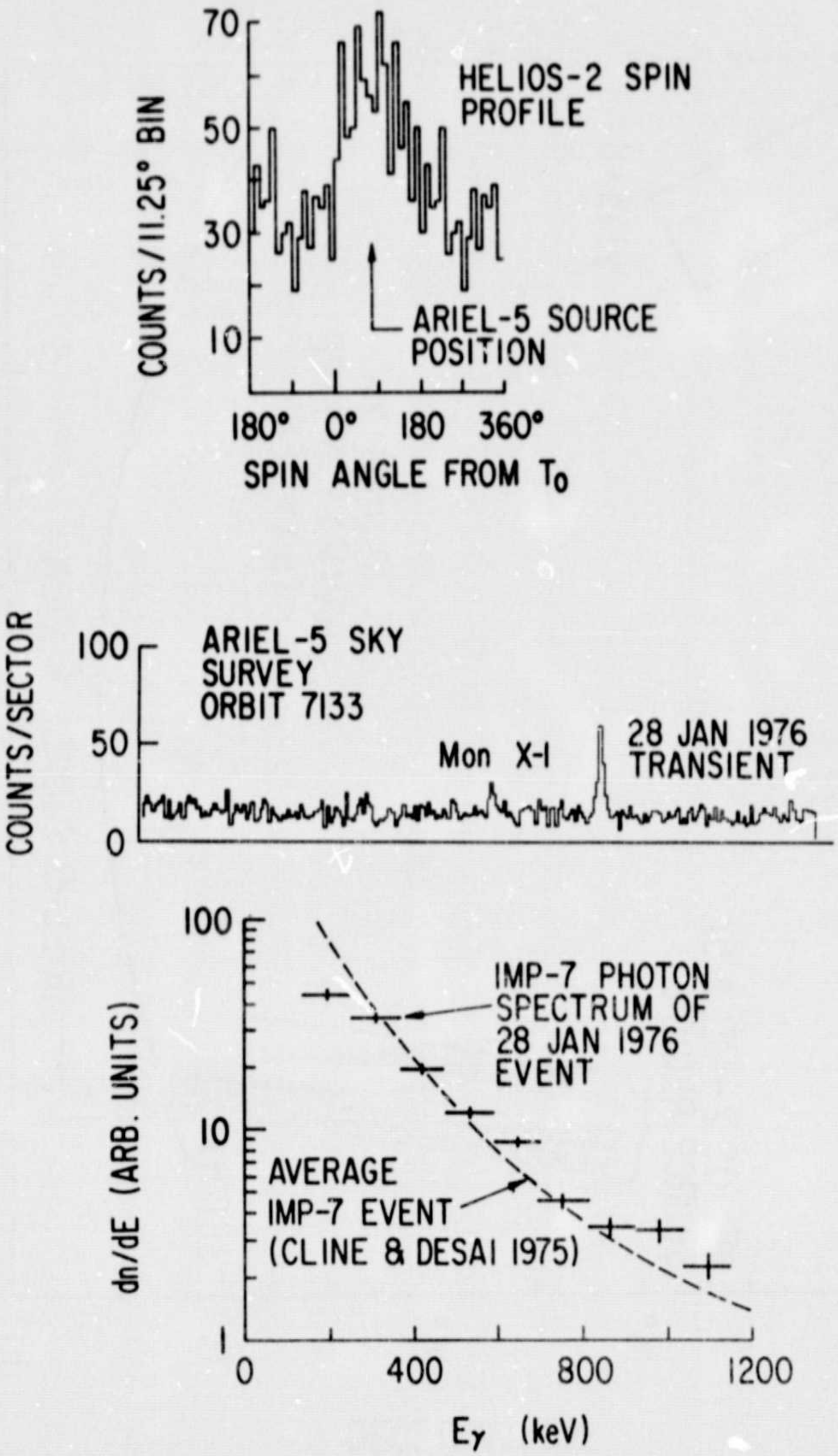

HELIOS-2
VELA-5A
1976
JAN. 28
T-T$_0$ (SECONDS)
COUNTS/0.99 SEC
COUNTS/0.25 SEC
-10
0
10
20
30
40
500
100
50
10
500
100
50
20

Fig. 1



70
50
30
10
COUNTS/11.25° BIN
HELIOS-2 SPIN
PROFILE
ARIEL-5 SOURCE
POSITION
180° 0° 180 360°
SPIN ANGLE FROM T0
100
50
0
COUNTS/SECTOR
ARIEL-5 SKY
SURVEY
ORBIT 7133
Mon X-1
28 JAN 1976
TRANSIENT
100
10
1
dn/dE (ARB. UNITS)
IMP-7 PHOTON
SPECTRUM OF
28 JAN 1976
EVENT
AVERAGE
IMP-7 EVENT
(CLINE & DESAI 1975)
0 400 800 1200
Eγ (keV)

Fig. 2

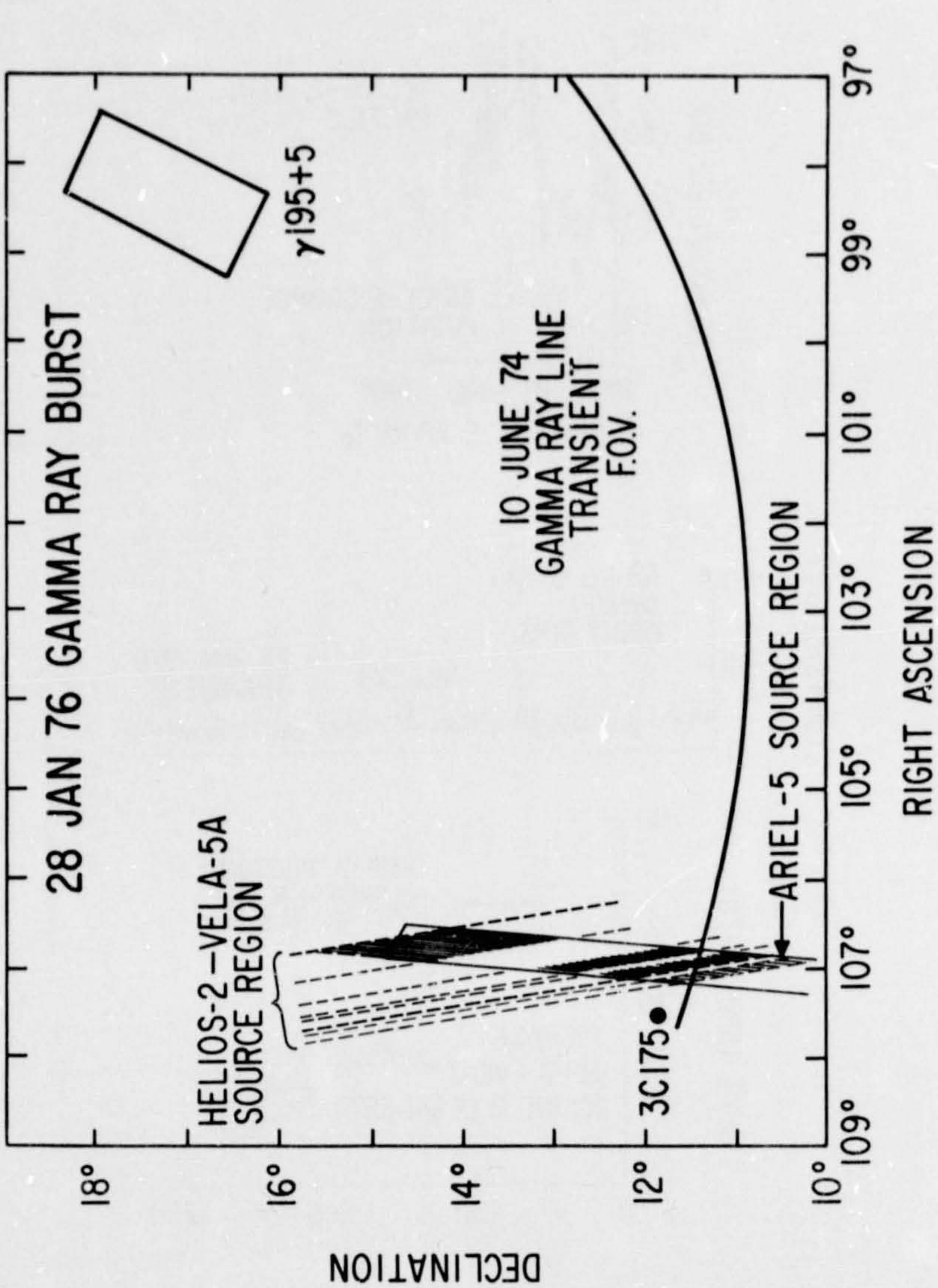

28 JAN 76 GAMMA RAY BURST
HELIOS-2—VELA-5A
SOURCE REGION
γ195+5
10 JUNE 74
GAMMA RAY LINE
TRANSIENT
F.O.V.
ARIEL-5 SOURCE REGION
3C175
DECLINATION
RIGHT ASCENSION
18°
16°
14°
12°
10°
109°
107°
105°
103°
101°
99°
97°

Fig. 3