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Gamma-Ray Burst Observations from Helios-2

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Abstract

Observations of five gamma-ray bursts made with the solar orbiter Helios-2 are reported. Wavefront timing from Helios-2, at distances of up to 1.98 AU, to Vela-5A and -6A, in Earth orbit, provides source location bands as narrow as 2 arc minutes, although several degrees in length. The burst intensities and time profiles measured in interplanetary space by Helios-2 are the same as those observed near the Earth, ruling out a narrow-beam interplanetary origin model. Also, the source direction bands for these events are inconsistent with the directions of all known celestial  $\gamma$ -ray objects, x-ray bursters and high-energy gamma-ray source regions. The gamma-ray burst source objects therefore appear to form a distinct class from all lower energy x-ray or higher energy  $\gamma$ -ray emitters.

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## Introduction

The outstanding mystery of gamma-ray bursts has continued since their discovery (Klebesadel et al., 1973) due to the persistent lack of source information. For several years, all gamma-ray burst observations were circumstantial in nature; direction measurements made either by wavefront triangulation (Strong et al., 1974) or with collimated sensors (e.g., Wheaton et al., 1973; Palumbo et al., (1974) yielded very rough source positions. Further, no temporal or spatial correlations were found with other transient phenomena which might provide clues regarding the source process. The need for an accurate technique to determine precise source locations was therefore clear. Given the low frequency of occurrence ( $\approx 10/\text{year}$ ) of intense, Vela-type events and the impracticability of resolving weaker, more frequent events from balloons (e.g., Cline et al., 1977), the technique using interplanetary sensors for very long baseline triangulation evolved as the natural successor to Earth-orbiter arrays.

The solar orbiter Helios-2, launched on 15 January 1976 into an orbit of 0.29 AU perihelion and 1 AU aphelion, to distances of up to 2 AU from the Earth, carries the first instrument flown for this purpose. To date, 18 bursts have been observed both with the GSFC Helios-2 sensor and with other burst detectors. We report here five Helios-2 events observed in 1976 and 1977 for which the Vela-5A and -6A satellites provide the only other timing base; later events observed with Helios-2, the Solrad and Signe satellite series and HEAO-A are also being studied. In all cases, source fields  $\geq 1$  arc minute by several degrees result, in the absence of other interplanetary bases. Triangulation with Helios-2 and the recently launched Venus probes will ultimately provide source regions  $< 1$  arc minute square in size.

The events reported here show the same flux and temporal profile characteristics in deep space as observed near the earth, indicating a distant or cosmic origin. Their source positions are not found to be the same as any known celestial x-ray or high-energy  $\gamma$ -ray emitters, indicating an entirely new population of source objects.

#### Instrumentation

The detector flown on Helios-2 has been previously described in detail (Cline et al., 1979). It was designed to respond to the known Vela-type events with time profiles from 0.1 to 30 seconds in duration (Klebesadel et al., 1973; Strong et al., 1974) and with temporal variations that could be expected with much briefer durations. Accordingly, three command-adjustable trigger modes were used with a two-minute total time history memory capability and with temporal precision up to 4 milliseconds. Three triggers sample the rates of  $> 100$ -keV counts registered in the 1.5 inch diameter by 0.75 inch thick CsI crystal in  $\approx 4$ , 32 and 250 msec. This energy threshold is also command-adjustable. An occurrence of any trigger causes the count rates to be stored in three memories on different time scales following ' $T_0$ ' and to be held in three circulating memories prior to  $T_0$ . In this manner, precursor information is made available, providing continuous time histories throughout each event. As a result, time histories of 128 seconds duration with 0.25 second resolution, 16 seconds with 32-ms resolution, and 2 seconds with 4-ms resolution are provided, nested about the trigger time. This technique gives the optimum temporal resolution if the various detectors used in coincidence to observe a gamma-ray burst happen to trigger at about the same point in the time history. As it turns out, this is always seen to occur,

since the sensitivities of the Helios-2 and Vela-5A instruments are nearly identical.

The Helios-2 event trigger time initializes the gamma-ray burst time history. This time measurement is the critical parameter, since it provides, by comparison with the time history detected with another instrument, the time delay of the burst wavefront and hence the direction of the source. The times on the spacecraft are determined by knowing the ground-received times and subtracting the one-way photon travel time as determined from orbit measurements. The accuracy of this process is a few milliseconds. The calibration of the entire on-board measuring process is provided by artificial ground-commanded triggers of the gamma-ray burst detector. By knowing the time of command telemetry and the one-way photon travel time, the observed  $T_0$  is compared with that expected. Agreement has been obtained in all occasions of this exercise, giving complete confidence in the timing accuracy of the experiment. In addition, the roll modulation of each burst time history is calibrated with the on-board optical aspect. The magnitude of the modulation indicates the ecliptic (spin plane) source proximity and the phase independently confirms the timing measurement, modulo the 0.99-second spin period.

#### Data Analysis

The five gamma-ray bursts we discuss here occurred on 22 March, 7 April and 19 April 1976, and on 10 March and 8 July 1977. Figure 1 illustrates the Helios-2 and Vela 5-A time histories for each of these events. The first four Helios-2 temporal profiles are displayed in the form of intensity per 250-millisecond readings, so as to illustrate the  $\approx$  1-second roll modulation. Simultaneous 32-millisecond and 4-millisecond time histories allow for correction for this effect and permit timing comparisons with

accuracies depending on the resolution of the profiles. Since the Vela-5A temporal profiles are always obtained on a time base expanding geometrically from 16ms to 16 seconds, high accuracy comparisons are possible only for the initial portion where the Vela and Helios-2 timing resolutions are similar. This limitation generally results in  $\approx 100$  msec profile comparison accuracy due to counting rate statistical fluctuations. The fifth Helios-2 time history shown was obtained at nearly 2 AU from the Earth, behind the Sun, and was read out later at a time when low bit-rate telemetry was being used; its quality is therefore not equal to the others. This event was unusually long, exceeding the 1-minute post-trigger memory limitation. Its time history has been corrected to one reading per 0.99-second roll for purposes of illustration. Vela-6A triggered only on the 22 March 1976 event of these five. Its sensitivity is lower than that of Helios-2 or Vela-5A. Therefore, its spectral response, profile shape and relative triggering times are necessarily quite different. Since the Vela-5A to -6A separation is minimal, the intensity profile comparison provides a coarse source band intersection with confirms that given by the Helios-2 roll modulation and the Earth occultation information, but which adds no further directional accuracy. In addition, the IMP-7 satellite has provided differential energy spectra from  $\approx 0.1$  to 1.0 MeV for each of the burst events discussed here (Cline and Desai, unpublished). These spectra are entirely similar in their characteristics to those found in many earlier bursts (Cline and Desai, 1975), verifying their typical gamma-ray burst nature and adding weight to the earlier indication that all bursts have essentially the same event-average spectrum.

The determination of the source direction of a burst depends on the wavefront arrival time difference and the distance between the two spacecraft. The source field is within the width  $\Delta\theta$  of the ring of opening half angle  $\theta$  described about the coordinates of Helios-2, as observed from Vela-5A. Each is defined by  $\theta \pm \Delta\theta = \cos^{-1} (T_V - T_H \pm \Delta T)c/R$ , in which  $T_V$  and  $T_H$  are the fitted wavefront detection times at Vela-5A and Helios-2,  $\Delta T$  is the total error in this fit and  $R$  is the distance between the two spacecraft. This ring is orthogonal to the ecliptic plane and is in fact bisected by the Helios-2 spin plane, since the ecliptic plane is both the spacecraft spin equator and the orbit plane of Helios-2. Thus, the solar ecliptic longitude of the burst intensity maximum as seen in the spin modulation profile, calibrated by the on-board optical aspect, uniquely defines a celestial source region. One low ecliptic latitude segment is defined if there is a large roll effect and, conversely, minimum roll amplitude leaves two symmetric high ecliptic latitude segments. If the ring has a large opening angle, then the ecliptic longitude of the source is nearly independent of source position on the ring, and provides one of two spin azimuths, which always agrees with the source ecliptic longitude given by the solar aspect.

The 76 April 7 event was detected with OSO-8 (R. Becker and P. Serlemitsos, pri.comm.) when the Goddard x-ray astronomy sensor was viewing the region of the galactic center. This observation is in excellent agreement with the Helios-2 profile roll maximum observed near  $\ell_{II} = 0$ . The 76 April 19 event was also detected by OSO-8 (B. Dennis and K. Frost, pri.comm.) with the Goddard solar x-ray detector, providing an above horizon region agreeing with the profile roll maximum segment listed in the Table. The 76 March 22 event was not observed by OSO-8, but surely should have been since it is more intense than either of the April events, thereby giving an Earth obscuration

region. This event was, however observed with the MIT x-ray instrument on the SAS-3 satellite (W. Lewin, pri.comm.), which provides an above-horizon region that is in agreement with the OSO-8 below-horizon region and with the Helios-2 roll profile maximum. The 77 March 10 event was observed both with the OSO-8 solar x-ray sensor and with the x-ray instrument on SAS-3, giving above-horizon regions which agree with the Helios-2 ecliptic plane preference, as listed in the Table. There are no analogous results for the 77 July 8 event, leaving that entire ring as source field. However, the small value of its maximum ecliptic latitude agrees with the presence of a spin modulation.

Table 1 lists the burst times, the spacecraft separations, the wavefront delays, the 1950.0 celestial coordinates of the source cone axes, and the burst source band locations and dimensions. The limits on the source rings obtained from earth-occultation measurements are exact, whereas those from the ecliptic longitude measurements obtained from the Helios-2 roll modulation are shown as approximate.

### Results

Several conclusions follow from the analyses of these events. First, the intensities and temporal profiles appear to agree over distances of up to 0.7 AU, taking into account the projected width,  $R \cos(90-\theta)$ , of the wavefront. This observations rules out the relativistic dust grain model predicting narrow ( $\approx 0.01$ -AU in extent) focussed beams of gamma rays originating within the distant solar system (Grindlay and Fazio, 1974). Second, the source regions, as shown in Figure 2, are not concentrated at low galactic latitude, consistent with previous indications of the absence of an apparent galactic source distribution (Strong and Klebesadel, 1974).

In fact, the six events shown, including one previously published (Cline et al., 1979), would fit better an inverse intensity relation to galactic latitude. This would indeed provide no support for a disk population model, but only consistency with a very nearby or a metagalactic isotropic source distribution.

Third, testing the source directions of known celestial x-ray and  $\gamma$ -ray emitters for consistency with the source ring segments for these five events has not produced any agreement. No steady or transient x-ray source in existing catalogs has a position that is within several resolution widths of the source regions listed, even though two of the segments cross the galactic plane where x-ray sources are most abundant. The locations of the high-energy gamma-ray emitters observed with SAS-2 (Kniffen et al., 1977) and COS-B (Hermsen et al., 1977) cluster along the galactic plane, and are all inconsistent with these burst locations. Thus, we conclude that gamma-ray burst emitters appear as a separate class of source objects and not as a transient manifestation of galactic x-ray or gamma-ray emitters. Finally, a wide variety of other source catalogs were tested for consistency--white dwarfs, nearby stars, etc. The lack of any agreement serves only to heighten the mystery of gamma-ray bursts.

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Helios II - Vela-5A Gamma Ray Bursts: Source Error Fields

Burst Date	Size ( $\text{erg cm}^{-2}$ )	UT at Earth (sec)	Spacecraft Separation (light-sec)	Wavefront Delay (seconds)	Cone Axis Coordinates $\alpha$ 1950 (degrees)	$\delta$ 1950 (degrees)	Angle Between Source & Cone Axis (degrees)	Segment Limits $\theta$ min $\theta$ max (degrees) (degrees)
1976 Mar. 22	$2 \times 10^{-4}$	55528	209.523	$89.39 \pm 0.15$	184.352	- 1.967	$64.75 \pm 0.05$	-5 33
1976 Apr. 7	$4 \times 10^{-5}$	10464	354.507	$5.07 \pm 0.10$	1.561	+ 0.715	$89.181 \pm 0.016$	$\approx -15 \approx 34$
1976 Apr. 19	$2 \times 10^{-5}$	26771	550.612	$454.03 \pm 0.08$	12.777	+ 5.487	$34.453 \pm 0.015$	123 $\approx$ 200
1977 Mar. 10	$7 \times 10^{-5}$	38394	165.873	$79.46 \pm 0.20$	29.160	+11.932	$61.38 \pm 0.08$	$\approx 225 \approx 315$
1977 July 8	$2 \times 10^{-4}$	46230	985.923	$952.96 \pm 0.27$	105.258	+22.676	$14.86 \pm 0.06$	- - - -

Table 1. Gamma ray burst source fields, as defined by the celestial ring segments, together with the input spacecraft separations and wavefront time delays, and the identifying burst dates and approximate Earth times. The smallest source field celestial areas are  $\geq 1$  square degree.

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FIGURE CAPTIONS

Figure 1 - The Helios-2 and Vela-5A time histories of five gamma-ray bursts. For the first four events, a 0.25-sec. count rate integration time base is used for the Helios-2 data, with the early portions of the geometrically expanding Vela count rate scheme converted accordingly, for illustration. The last event uses a 0.99-sec. Helios-2 spin-period time base. Background has been subtracted in all cases. The  $\approx$  1-sec. roll modulation is obvious in the March 22 event, and appears as a suppression of the first peak and of the leading edge of the second peak in the April 7 event, when the detector is found to be pointed away from the source. The single narrow peak in the April 19 event agrees with a source-oriented detector position in that case. Given the projected wavefront extents of up to 0.7 AU for these events, when the two spacecraft were separated by up to 2 AU, no statistically significant departure in profile or in total intensity is found for support of an interplanetary, narrow photon beam model. The March 22 event time history appears to be anomalously regular in its smooth, single-decay structure, as compared with the more random features of varied extent found in the other four shown here and in a large number of other events (Cline et al., 1979; Metzger et al., 1973; Cline, unpublished).

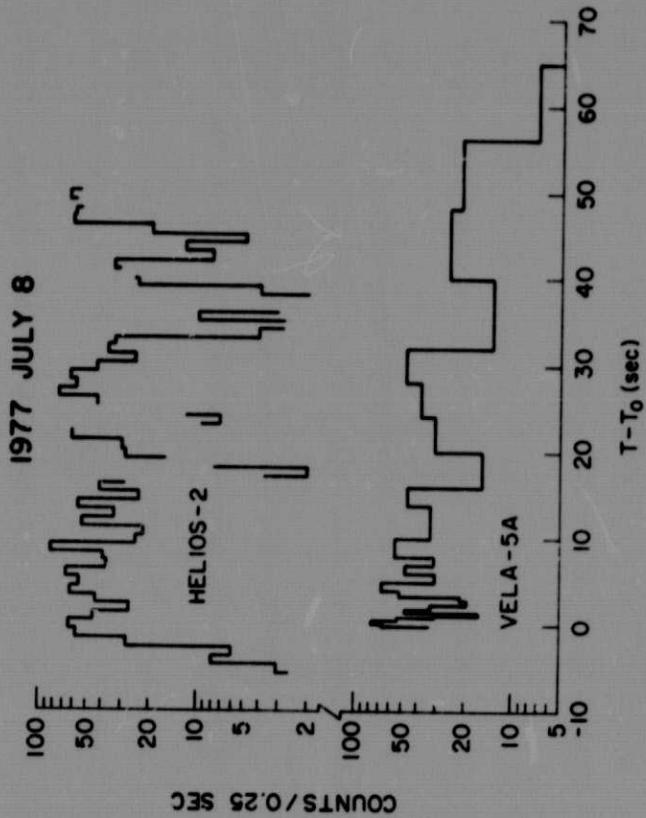
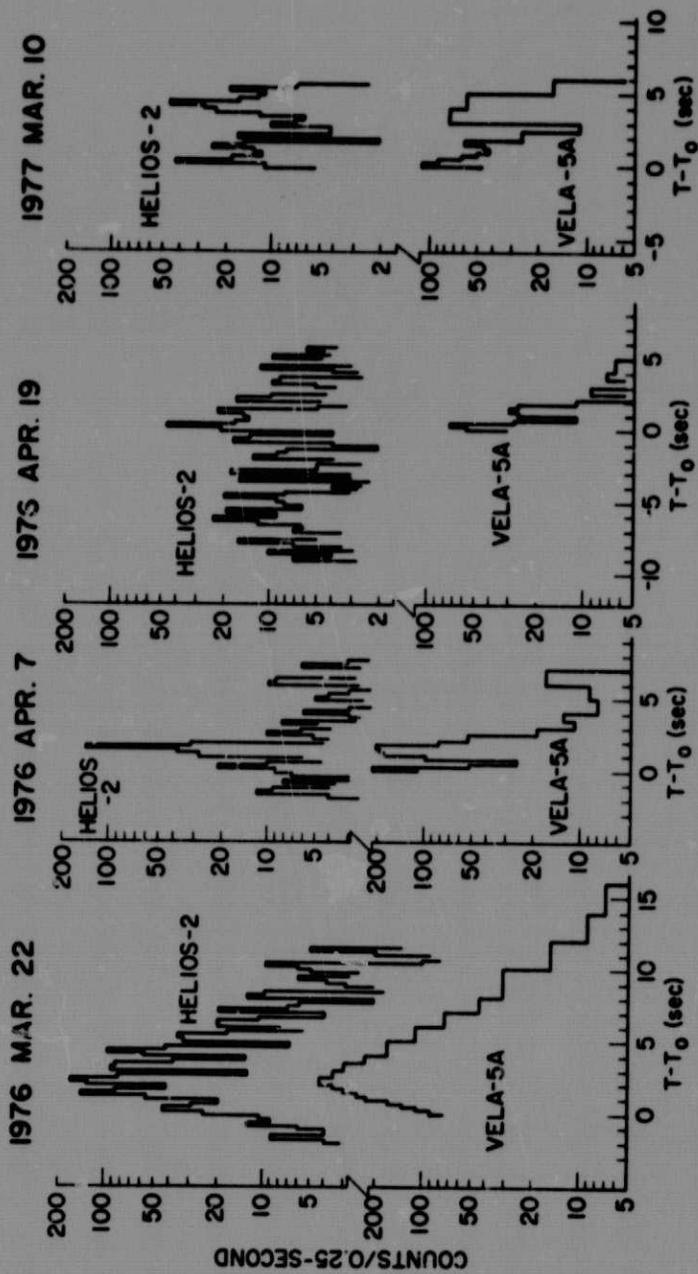
Figure 2 - The source fields of the five gamma-ray bursts analyzed here, shown in a galactic coordinate, equal solid angle representation. The source field of a previously published Helios-2 - Vela burst event, also observed with Ariel-5 (Cline et al., 1979) is also shown. In spite of the proximity of several of these bands to the galactic plane, there is no consistency with the directions of any other x-ray or gamma-ray source objects. The 76 April 7 and 77 July 8 source bands could conceivably overlap certain earlier gamma ray burst source regions; considering the size of those source regions (Klebesadel and Strong, 1976), this is not considered to be evidence that burst sources are repeating emitters.

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Fig. 1

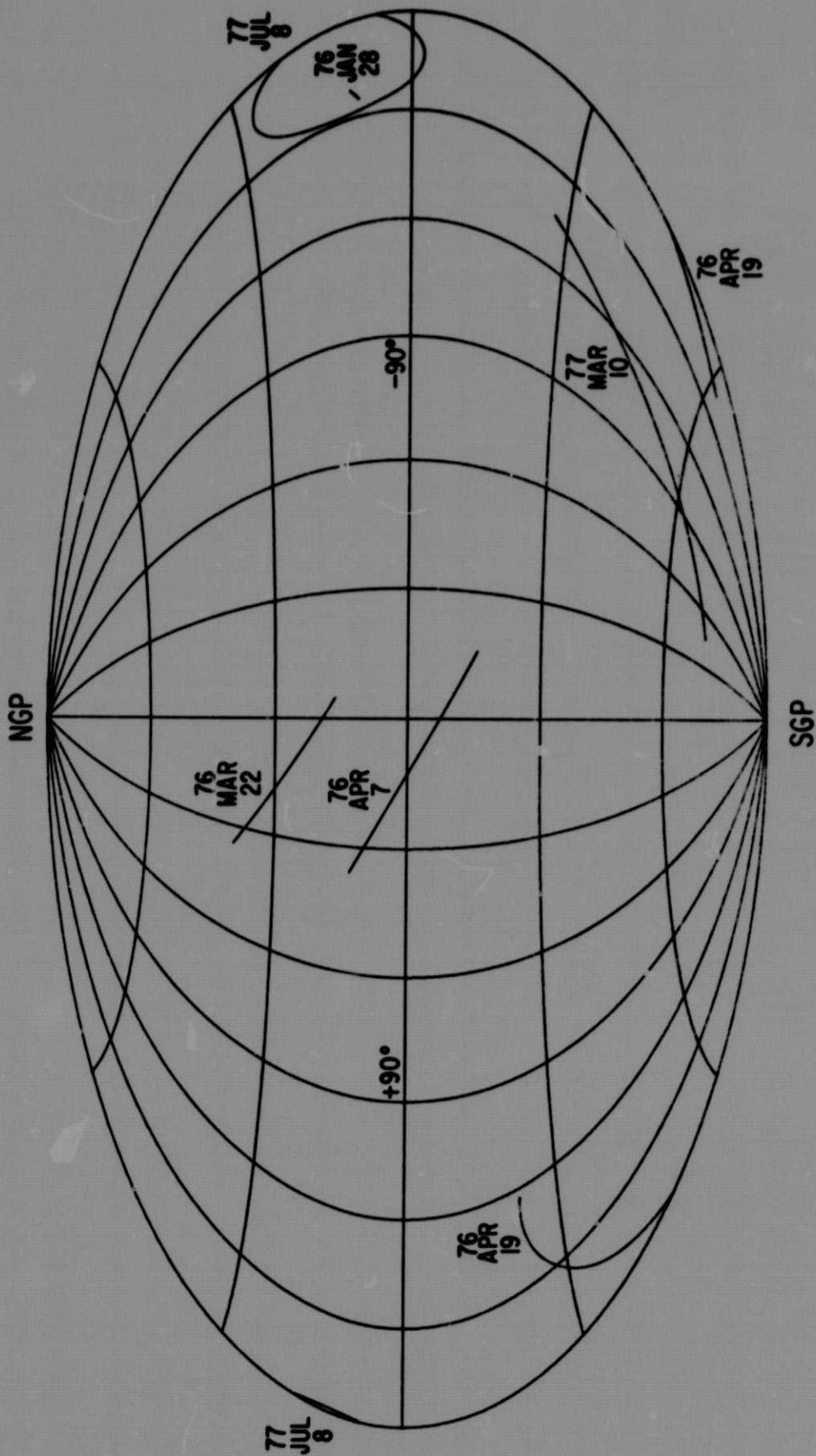


Fig. 2

## BIBLIOGRAPHIC DATA SHEET

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