THE ASTROPHYSICAL JOURNAL, 185:L1–L5, 1973 October 1

ENERGY SPECTRA OF COSMIC GAMMA-RAY BURSTS

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Received 1973 July 24

ABSTRACT

We report spectral measurements of six cosmic gamma-ray bursts in the energy region 0.1–1.2 MeV, made using a semi-omnidirectional X-ray detector on IMP-6. These measurements confirm the hard X-ray or gamma-ray nature of the bursts, as inferred from the original observations by Klebesadel *et al.*, and show that their maximum energy release is in this several-hundred-keV region. Each burst consists of several 1- or 2-second pulses each with the characteristic spectrum of a ~150-keV exponential, followed by a softer decay. There is no evidence of line structure in this energy region, or for a marked change in the energy spectrum within a given pulse. Event size spectra are estimated for galactic and extragalactic models; the total emission is consistent with present measurements of the diffuse bacground, and is unlikely to account for any spectral feature in the few-MeV region.
Subject heading: gamma rays

I. INTRODUCTION

The occurrence of intense, several-second duration bursts of 0.1- to 1.2-MeV cosmic gamma rays, recently found using multiple Vela satellites (Klebesadel *et al.* 1973), has been confirmed with measurements from the IMP-6 satellite. Observations regarding times of occurrence, photon flux, and temporal and spectral characteristics of the bursts are entirely consistent. In particular, since the IMP-6 instrument incorporates a hard X-ray detector with active particle rejection and full-time omnidirectional particle intensity monitoring, the results fully confirm and establish the hard X-ray or gamma-ray nature of the incident flux.

Detailed differential energy spectra were obtained with the IMP-6 for six of the eight known events occurring during the 1971 March to 1972 September lifetime of the instrument. All of these are multiple-pulse events, with several seconds separation between distinct pulses of one or two seconds duration. The pulse spectra do not obey single-index power laws in energy, but can be simply represented by exponentials in photon flux throughout the 100–1200 keV region. The characteristic energies at maximum intensity appear to cluster near 150 keV, with indications that departures from this value can be interpreted as circumstantial, due to attenuation when the source is at great angles from the detector axis. These burst pulses appear to ride on a softer component that exhibits a longer decay time constant, and has a characteristic exponent near 75 keV. There is no evidence for monoenergetic line structure in the several-hundred-keV region, or for marked changes in the spectrum with time during a single pulse. Size spectra can be estimated to predict the frequencies of occurrence of smaller events for both a galactic model (e.g., a new class of gamma-ray flare star) and an extragalactic model (e.g., supernovae). In either case the total emission is below the value currently obtained for the diffuse celestial X-ray background, and is unlikely to account for any of its spectral features.

II. INSTRUMENTATION

The IMP-6 satellite was launched in 1971 March 14 into an elliptic orbit with an initial apogee of over 200,000 km. Gamma-ray monitoring was provided on a nearly continuous basis, except for passes every 4.14 days through the magnetosphere, lasting several hours each. The detector was in operation from launch until 1971 May 2, and again for the period from 1971 June 9 to 1972 September 27. The instrument used consisted of a 2.25-inch diameter by 1.5-inch thick CsI(Tl) crystal, entirely surrounded by a thin plastic scintillator for particle rejection, viewed by a single photomultiplier tube. In addition to full-time monitoring of the rates of total intensity, particle intensity, and gamma-ray intensity, energy spectra of incident gamma rays were measured by a 14-channel analyzer with simultaneous storage in all channels. The spectra were accumulated for one-half of the time, for each $\sim$6.3-s period from sunrise to sunset on the detector, determined by the optical aspect. This 50 percent duty cycle resulted in missing several of the very brief gamma-ray bursts. The spectral accumulation times were fixed at $\sim$5.1 s so that the $\sim$6.3-s lifetimes were asynchronously split into two or three intervals of shorter durations, making possible more than one spectral determination during some of the pulses. The gain of the system was cycled through four positions with changes at approximately one-week intervals for purposes of in-flight calibration, so that some of the bursts happened to be observed with a 69- to 1150-keV dynamic range and some with a 53- to 880-keV range. The primary purpose of this gamma-ray detector was use as a coincident annihilation spectrometer incorporated in a positron detector. The secondary objective was that of a solar-flare monitor, and it was in this mode of operation that these unexpected gamma-ray bursts were observed.

III. DATA OBSERVATION AND ANALYSIS

The times of occurrence of gamma-ray bursts observed with multiple Vela satellite coincidences were used to identify coincident increases in the IMP-6 gamma-ray intensity. Six of the eight Vela events were observed well above the omnidirectional background, and others being missed because of the 50-percent detector duty cycle. It is possible that other events, of intensity too low to exceed the Vela threshold triggers, may also be observable with the IMP-6 instrument. Figure 1 shows the response of the IMP gamma-ray detector to the event of 1971 June 30. During a several-second interval, the counts in the plastic scintillator (P) surrounding the gamma-ray crystal increased by about 50, while the neutral counts in the crystal ($\gamma\bar{P}$) simultaneously increased by about 18,000. Pulses satisfying the gamma-ray logic are fed to a multichannel analyzer, from which the outputs of three channels, added to provide the flux of 140 to 475 keV photons, indicate an increase during one $\sim$5-s interval of nearly 5000 counts from a total omnidirectional and secondary background of about 400 counts. This illustrates the remarkable intensity of the bursts, and shows that the response is entirely consistent with that of hard X-rays or gamma rays.

The times of occurrence and various properties of all Vela-IMP events observed during the IMP-6 experiment lifetime are listed in table 1. The temporal structures of the observed bursts, known from the Vela results, were compared in order to determine over which intervals in the event structures the IMP spectra were obtained. Since the IMP-6 satellite was spinning, an analysis was also made for each burst to determine in which direction the detector was facing, relative to the source, at the moment each spectrum was obtained. Each of the six events was observed by the Velas to have at least two distinct pulses of up to a few seconds duration, separated by intervals of several seconds. The time resolution of the IMP gamma-ray detector ($\sim$2.5 s) permitted obtaining individual spectra for many maximum-intensity pulses, and, for some cases, two separate spectra of a given several-second pulse. (Vela data

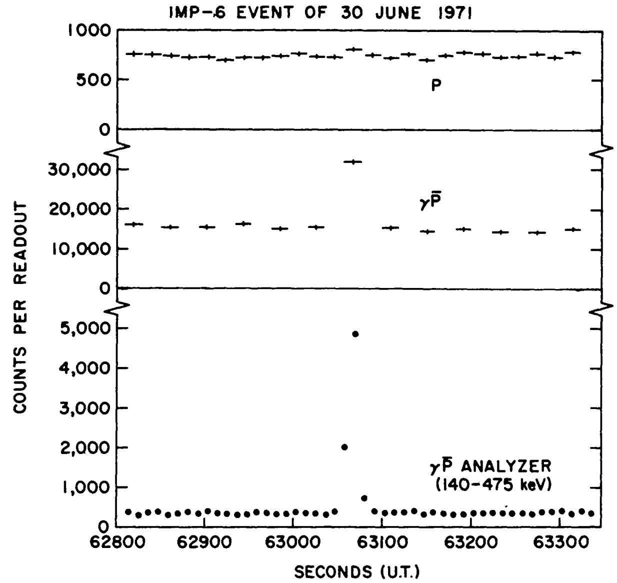

FIG. 1.—The response of the detector to a gamma-ray burst, as indicated by the plastic anticoincidence (P), the CsI gamma-ray detector ($\gamma\bar{P}$), and several channels added to give the 140–475 keV photon rate, where the gamma-ray energy response is maximized. Each point samples two differential energy spectra.

TABLE 1

CHARACTERISTICS OF GAMMA-RAY BURST SPECTRA

Event	Burst	I_0	E_0	Look Angle
1971 Mar. 15	Second max	1.9	156	Includes source ($\alpha \simeq 50°$, $\delta \simeq -30 \pm 10°$)
1971 Mar. 18	Decay of first	1.8	74	Spins through source
1971 June 30	First max	0.7	276	Source below satellite horizon
1971 June 30	Second max	5.5	142	Spins through source
1971 June 30	Decay of second	0.7	110	Spins through source
1972 Jan. 17	Decay of first	0.10	138	Source position undetermined
1972 Jan. 17	Second max	0.35	184	Source position undetermined
1972 Jan. 17	Decay	0.11	170	Source position undetermined
1972 Mar. 28	First max	0.50	238	Source near or below horizon
1972 Mar. 28	Second max	0.55	176	Source position undetermined
1972 May 14	First max	0.8	166	Includes source ($\alpha \simeq 175°$ $\delta \simeq +77°$)
1972 May 14	Second max	0.8	152	Includes source

NOTE.—Exponential fits in dn/dE provide I_0 in units of photons cm^{-2} keV^{-1}, and E_0 in units of keV, both of which have systematic uncertainties depending on relative look angle.

show that a given maximum-intensity pulse can contain a variety of fast time variations [Klebesadel, Strong, and Olson 1973]; these are necessarily averaged over in the IMP spectra.) Figure 2*a* shows photon number spectra, dn/dE, for several of the bursts, as sampled on a 6.3-s half-spin basis. It indicates that, in this energy region, relatively good fits to these raw data are obtained to exponentials of the form $dn/dE = I_0 \exp(-E/E_0)$ photons cm^{-2} keV^{-1} $burst^{-1}$. The I_0 and E_0 values are listed in the table, along with the relative look-direction accuracies. The directions of origin of the six events are known with widely varying accuracy, but in the case of the June 30 event it is known that the first spectrum was recorded when the source was below the satellite horizon of the detector. Thus, the harder (250-keV) spectrum may be accounted for by attenuation of the lower-energy photons in the metal surface of the satellite. If that is also the case of the 1972 March 28 event, then all the pulses are consistent with 150-keV spectra. Two of the six events (1971 March 15 and 1972 May 14) have unambiguously known source directions which are not far from the center of the field of view, and these are definitely 150-keV spectra. In addition, the 1971 March 18 event and a number of decays of the other events, not listed, are consistent with softer spectra, suggesting that a slower-time-constant soft component is present in addition to the 150-keV peaks. Figure 2*b* (*insert*) shows the energy spectrum, or power spectrum averaged over the pulse burst duration, Edn/dE, of an event for which the source direction was known to be in the view direction. It is seen that the energy output is a maximum in this region. This may indicate that the photons released from the source objects are

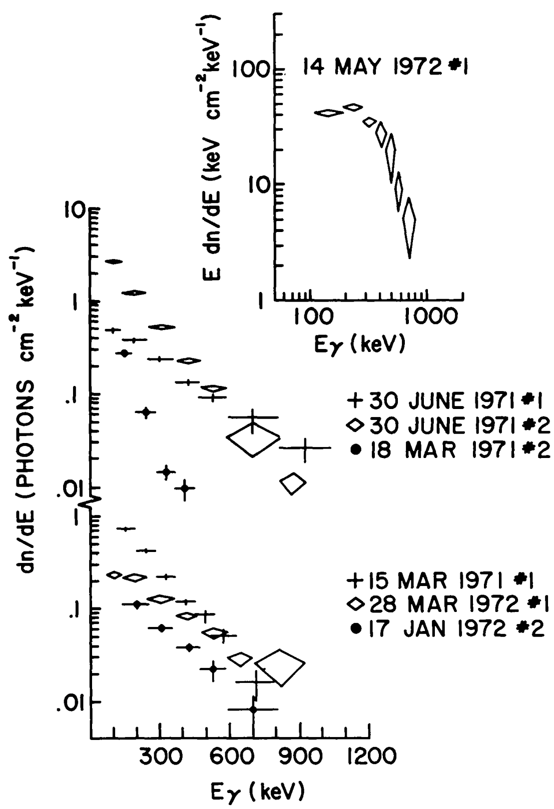

FIG. 2.—(*a*) Number spectra dn/dE, of several bursts, selected for the greatest variety of responses. The harder spectra are interpreted as due to attenuation of the incident beam by the satellite material in cases where the source was below the detector horizon (*b*) (*insert*) The energy spectrum, Edn/dE, of a directly observed event.

essentially gamma-ray in nature, not composing X-ray distributions with spectral tails in the gamma-ray region. If much softer X-rays are emitted in the primary burst, they most likely undergo relatively greater absorption near their region of origin.

IV. DISCUSSION

It is clear that the observed gamma-ray bursts represent an entirely novel form of cosmic energy release. The durations of the individual pulses are typically 1 to a few seconds, and the separations between pulses in a given burst are up to 20-odd seconds. The temporal structure might therefore be compared to that of solar flares, but with time scales one to two orders of magnitude shorter, suggesting a conceivable source origin of gamma-ray flare stars. The 150-keV energy spectra, including the one known case of the 1972 May 14 event which has a power law from 10 to 100 keV (Wheaton *et al.* 1973), contain too much emission in the X-ray region to fit $\sim$150-keV blackbody spectra, and yet too little emission in the lower energies to be compared to the typical steep X-ray spectra, having index of ~ -3 or more, of most hard solar flares and many celestial X-ray sources. For those pulses which were observed with sufficient temporal resolution to obtain more than one spectrum per pulse, there is no evidence for changes in the characteristic energy during its extent (not illustrated). Further, there is no evidence for line structure in this energy region. It is possible, however, that great improvements in energy and time resolution might show fine-scale spectral variability with a variety of monochromatic lines, which average out over 2-s summations.

An integral size spectrum can be constructed, assuming a power law with index -1.5, normalized to six or eight events per 1.5 years with sizes greater than 10^{-4} ergs cm^{-2} for the energy region above 100 keV. Since the 18 known events have source directions compatible with isotrophy (Strong and Klebesadel 1973) rather than with, e.g., galactic plane clustering, the source objects must either have distances in the tens to hundreds of parsecs if galactic, or, if extragalactic in nature, have distances of more than several Mpc. Thus, this size spectrum can be normalized for these two models in order to obtain predictions of the frequencies of occurrence of smaller events. In the case of extragalactic sources—e.g., gamma-ray rich and optically poor supernovae or other large collapsing objects—a summation of all emissions up to cosmological distances produces a total isotropic background intensity which is below the presently observed diffuse cosmic background in this energy interval. Thus an extragalactic origin cannot be ruled out. Further, if all sources have spectra with $\sim$150-keV exponentials, then the total cosmic spectrum will not extend into the several-MeV region with sufficient intensity to explain the bump in the diffuse cosmic background observed (Trombka *et al.* 1973) at those energies.

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