PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Cosmic γ-ray Bursts

G. Vedrenne

Phil. Trans. R. Soc. Lond. A 1981 **301**, 645-658
doi: 10.1098/rsta.1981.0146

Phil. Trans. R. Soc. Lond. A **301**, 645–658 (1981)
Printed in Great Britain

Cosmic γ-ray bursts

By G. Vedrenne
Centre d'Etude Spatiale des Rayonnements – C.N.R.S.–U.P.S., B.P. 4346–9, *avenue Colonel Roche*, 31029 *Toulouse Cedex, France*

Although γ-ray bursts were discovered over ten years ago, the study of their temporal structure, their spectrum and their lg N against lg S distribution have still not enabled scientists to determine their origin.

Since 1978, however, considerable progress has been made in the accuracy of locating bursts by triangulation methods, by using a large network of observations made by the Helios B solar-orbiting satellite, the interplanetary spacecraft Pioneer Venus and Venera 11 and 12, ISEE-C and Earth-orbiting satellites. With the great distances between these various measuring points, it can be hoped that an accuracy of the order of one minute of arc will be attained for many events observed in 1979 and 1980. This accuracy has already been surpassed for the March 5, 1979 event.

In this paper an analysis of the latest observations, and results on the exact location of the arrival directions of several bursts will be presented, along with the evidence they provide about the origin of this radiation.

Introduction

At the end of 1972 Klebesadel, Strong and Olson (Klebesadel *et al.* 1973; Strong 1973) demonstrated the existence of γ-ray bursts from observations made with the Vela satellites. During the last decade, the main characteristics of these γ-ray bursts have been studied. However, since their spatial origin is unpredictable, omnidirectional detectors have generally been used to detect them. Thus the location of γ-ray bursts on the celestial sphere has only been possible by using the triangulation method, a technique that relies on a measurement of the time of arrival of a burst at different points in space.

Until 1975, all observations were made by Earth-orbiting satellites, and consequently the distance between the various points of observation did not allow a very good location accuracy with the triangulation method. This was particularly true since the experiments were not designed for this type of study and the absolute time measurements of the bursts were often inaccurate. In January 1976 the launch of the heliocentric satellite Helios-2 provided the first opportunity to place into orbit a piggy-back experiment which was especially designed for the study of γ-ray bursts and which allowed a more precise determination of the emission regions, owing to the large distance (up to 2 AU) between the spacecraft and the Earth. However, only in 1978, with the launch of Pioneer Venus Orbiter in May, of ISEE-C in August, of Venera 11 and 12 in September, and also of Prognoz 7 in November did it become possible to localize γ-ray bursts with an accuracy of several minutes of arc or less. An accurate location is very important because it can allow an identification of the γ-ray burst source with a known object. The distance of the source may then be determined and thus the intrinsic amount of energy contained in a burst. At the same time very important information on the source may be obtained in other spectral regions and so help to understand the conditions and the mechanisms of emission.

An excellent recent review of observational results on γ-ray bursts appeared in 1978 (Hurley 1980) so the present discussion will be limited to the most interesting results over the past two years, with emphasis on the accurate location of γ-ray bursts. The first section of this paper will be devoted to a discussion of the main characteristics of γ-ray bursts, by considering the more recent data, while §2 will treat precise locations of several events. Since the results obtained to date do not answer the important question of what the emission mechanisms are, the review of Ruderman (1975) on the possible origins of γ-ray bursts remains valid, and the new results only place some constraints on the models; these constraints will be discussed in §3.

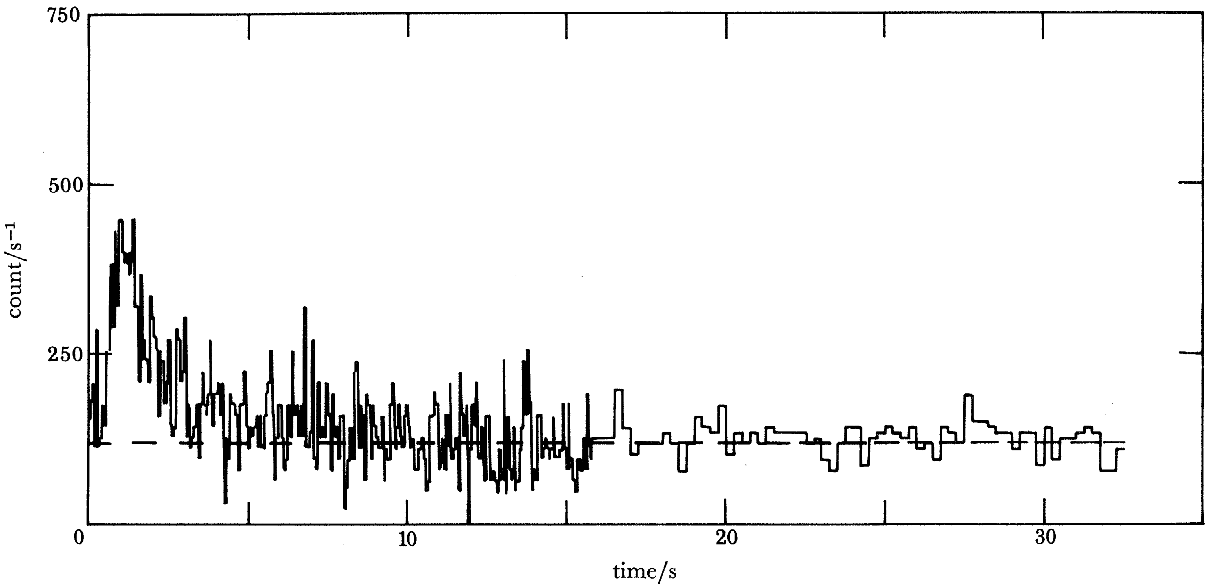

FIGURE 1. Example of a short event (September 18, 1978) observed with the Franco-Soviet experiments Signe on Venera 11.

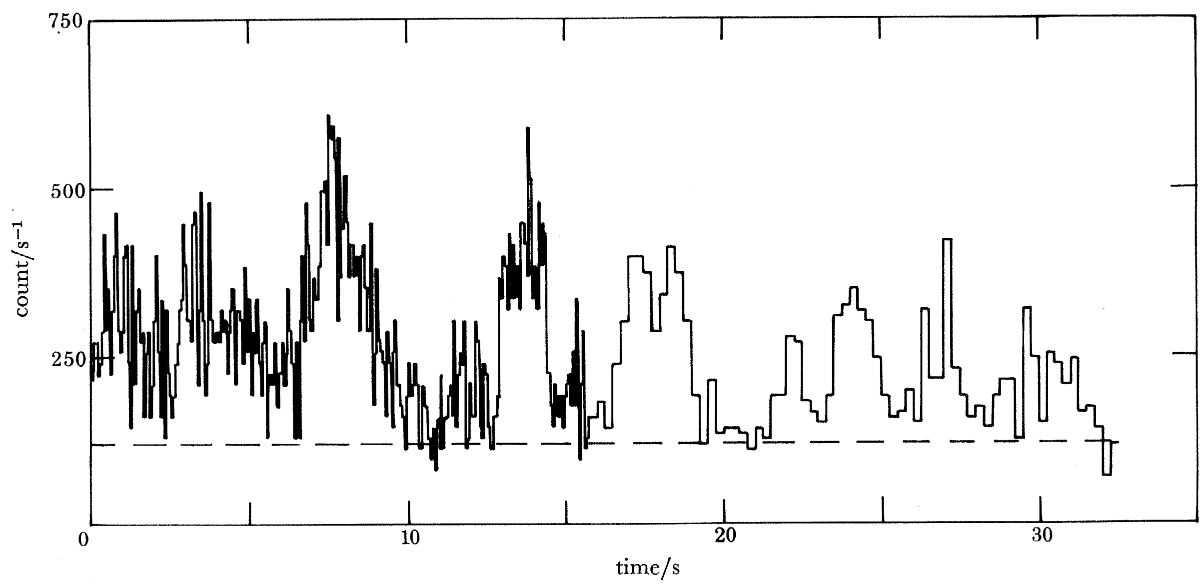

FIGURE 2. Example of a highly structured event (July 31, 1979) observed with the Signe experiments on Venera 12.

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1. General characteristics of γ-ray bursts

Time structures

To the 62 confirmed γ-ray bursts discovered during the period 1967–77, more than 40 can be added that were discovered between September 1978 and December 1980 by the interplanetary network which includes: Pioneer Venus Orbiter, ISEE-C, Helios B, Vela, Prognoz 7, Venera 11 and 12 (Franco–Soviet programme; Signe experiments). For this period more events were reported by the Leningrad group which has experiments on Venera 11 and 12 (Mazets *et al.* 1979*d*, *e*, 1980*c*). The large number of γ-ray bursts discovered during this period of less than two years corresponds to an observation period with a large sky coverage: on average at least six instruments were in orbit simultaneously. Moreover, as the equipment was more sophisticated it allowed the general characteristics of these bursts to be well studied. Thus burst durations were observed to vary from several hundred milliseconds to about 100 s, with numerous peaks evident in a single event, some lasting as little as about 10 ms (Laros *et al.* 1977). Figures 1 and 2 give two examples of very different bursts: one short, one very long and highly structured.

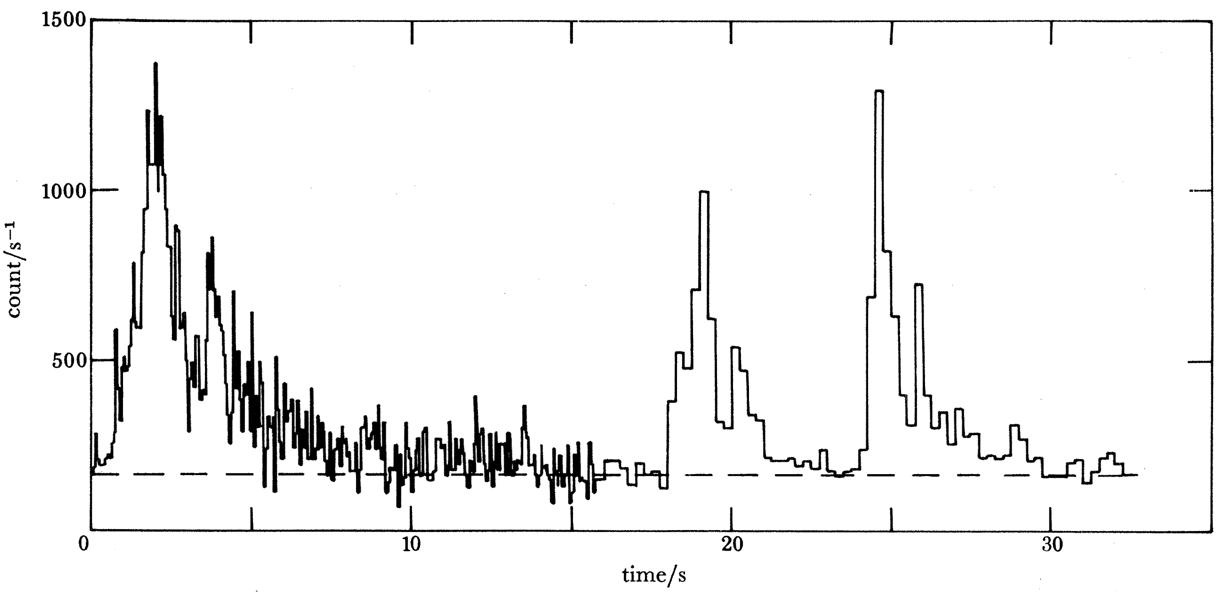

Figure 3. Example of a recurrent event (January 13, 1979) observed with the Signe experiments on Venera 12.

Attempts to classify the events (Barat *et al.* 1980) and to find similarities in the time profiles of γ-bursts have been made (Desai *et al.* 1980). It appears that numerous events display a two-peaked structure with 2–3 s between peaks; this double peak structure can even be recurrent inside one event (figure 3), although a study by Pizzichini (Pizzichini 1980) on possible periodicities gave no clear conclusion on this point. Only the March 5, 1979 event, which is quite unusual from many points of view, reveals a distinct periodicity of 8 ± 0.02 s (Terrel *et al.* 1980; Barat *et al.* 1979; Mazets *et al.* 1979*b*; Cline *et al.* 1980*a*). It is also the only event whose rise time to maximum is less than 0.25 ms, while its intensity is greater by a factor of ten than any event observed to date. In this regard, it should be noted that a very fine time structure at the 2 ms level has been found for the first time, for the event of June 13, 1979, in the Venera 11 and 12 experiments (figure 4).

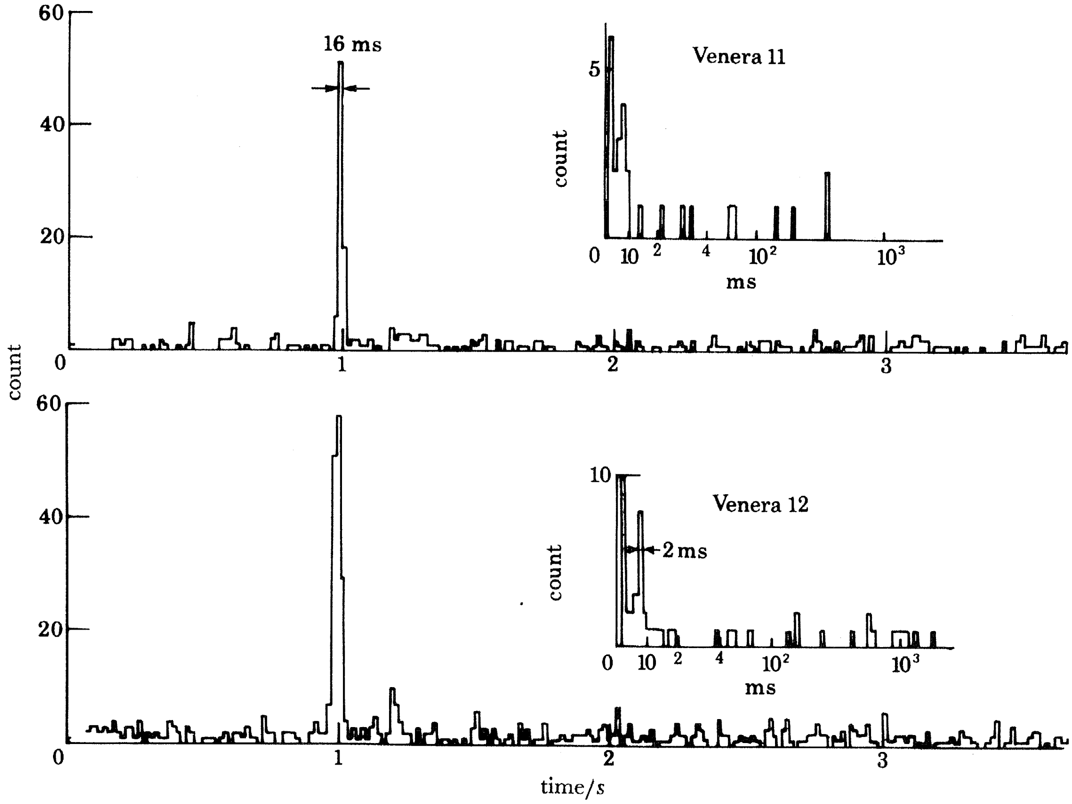

FIGURE 4. June 13, 1979 event showing the presence of peaks which last for about 2 ms (Signe experiments, Venera 11 and Venera 12).

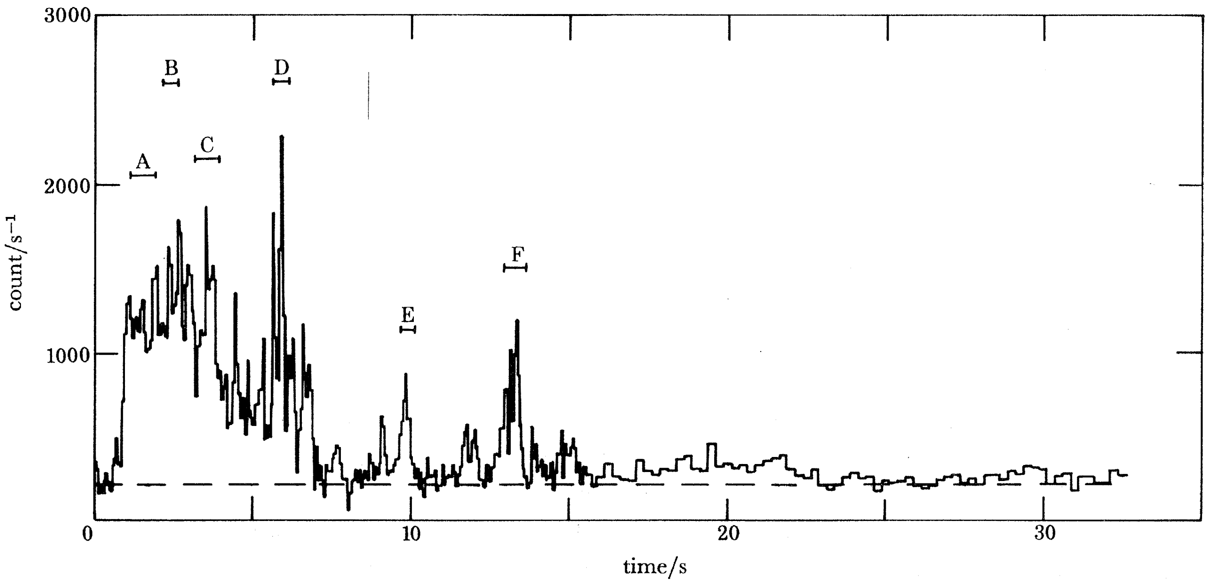

FIGURE 5*a*. Time profile of the November 19, 1978 event (Signe experiments, Venera 12). A–F indicate the times where spectra were measured.

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It has also been noted that some events may come from the same source (Golenetskii *et al.* 1979; Mazets *et al.* 1979*a*); for instance three events observed on March 6, April 4, and April 24, 1979 seem to come from the region of the March 5 event, and have similar time histories. Other possibilities of recurrence have been given by Mazets & Golenetskii (1980) as well as by Klebesadel & Strong (1976) for two events, 71–02 and 72–02, which might both have come from the Cyg X-1 region. While the possibility of recurrent events is interesting, the large error boxes associated with the bursts mentioned above preclude currently any definite conclusion.

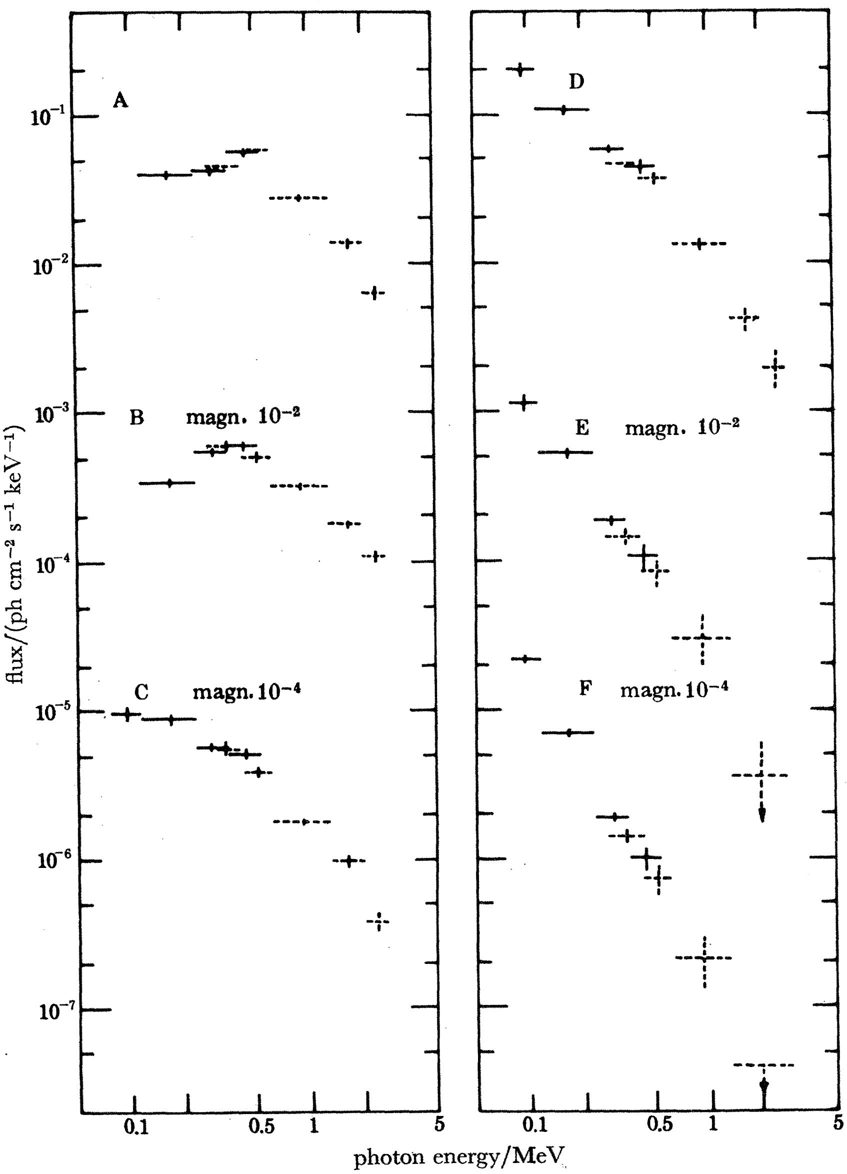

FIGURE 5*b*. Evidence of spectral variation during the November 19, 1978 event. —+—, Venera 12; – –+– –, Venera 11. A–F correspond to letters in figure 5*a*.

Spectra

The general characteristics of the spectra of many bursts were used by Hurley (1980) to define a standard spectrum. Cline *et al.* (1973) had in fact found very early on a great resemblance between spectra and they have confirmed this general trend for many events (Cline & Desai 1975, 1976). However, other recent spectral measurements (Barat *et al.* 1980) seem to indicate clearly that there exists a wider range of γ-ray burst spectra than was previously suspected. Moreover, fine spectral analysis during a single event often shows a pronounced spectral evolution with time (Barat *et al.* 1980; Knight *et al.* 1980) (figure 5*b*). This variability had already been noted by several authors for the low energy (below 200 keV) region (Wheaton *et al.* 1973; Imhof *et al.* 1974, 1975; Kane & Anderson 1976; Kane & Share 1977). However, some events, such as that of April 27, 1972, whose spectra have been analysed in different parts of the burst (Gilman *et al.* 1980), are compatible with an absence of variation. But here, again, a great diversity in the behaviour of γ-ray bursts can be seen. This diversity also appears in the presence of characteristic spectral lines. For example, many lines have been reported by Mazets & Golenetskii (1980) for the events on September 18, April 18, and November 4, 1978, January 16, March 5, June 22, and November 19, 1979, at energies between 400 and 460 keV. For the last event a line at 420 keV was observed by a Germanium spectrometer on the ISEE-C spacecraft and a line at 740 keV was also reported (Teegarden & Cline 1980*a*, *b*). These two lines are consistent with a common redshift if the parent lines are assumed to be the positron annihilation line (511 keV) and the first excited state of iron (847 keV). The same sort of redshifted lines had already been reported for a transient event (Jacobson *et al.* 1978) as well as from the Crab (Leventhal *et al.* 1977). A redshift of $z \approx 0.25$ is consistent with surface production by a $1\,M_{\odot}$ neutron star. Recently Mazets *et al.* (1980*b*) have reported the presence of cyclotron absorption lines in γ-ray bursts, which suggests the existence of a strong magnetic field (2 to 6×10^{12} Oe†). Such lines are extremely important for defining the type of object that produces γ-ray bursts, and therefore should be searched for in future experiments with high energy resolution detectors.

A good determination of the continuum is equally important. For example, the very well defined spectrum of the April 27, 1972 event, and its good fit by a thermal bremsstrahlung spectrum from a very hot plasma with low optical depth for Compton scattering, allowed an estimate of the upper limit of the distance for the source (Gilman *et al.* 1980). Similarly, the observations of spectra extending above 1 MeV are extremely important, since they too add constraints to source distances. Schmidt (1978) has shown that a non-relativistic γ-burst source that emits isotropically cannot be of extragalactic origin if there are γ-rays above 1 MeV in the burst, because the required photon density in the source would be so high that the medium would be optically thick in the megaelectronvolt region, simply owing to γ–γ pair production.

Burst intensity distribution

Recent observations of γ-ray bursts of weak intensity (White *et al.* 1978; Nishimura *et al.* 1978; Fishman *et al.* 1978; Agrawal *et al.* 1979; Beurle *et al.* 1980) as well as the recent results of Mazets from the Venera 11 and 12 spacecraft (Mazets *et al.* 1980*a*) can be used to define more precisely the lg *N* against lg *S* curve, which gives the number of bursts per year $N\,(>S)$ with time-integrated flux greater than *S* (erg‡ cm^{-2}) (figure 6).

† 1 Oe = $10^3\,(4\pi)^{-1}\,\mathrm{A\,m^{-1}} \approx 79.58\,\mathrm{A\,m^{-1}}$. ‡ 1 erg = 10^{-7} J.

Moreover, thorough theoretical analyses of the lg N against lg S distribution have recently been developed for different models by Fishman (1979) and by Jennings & White (1980). The comparison of the predicted and observed distributions seems to exclude an extragalactic origin, and favours a disc distribution with a uniform space density of sources and a characteristic height of about 400 pc. It had been claimed that these results are relatively insensitive to the luminosity function of bursts (Yoshimori 1978), but more recent work seems to prove this is not correct (Jennings 1980).

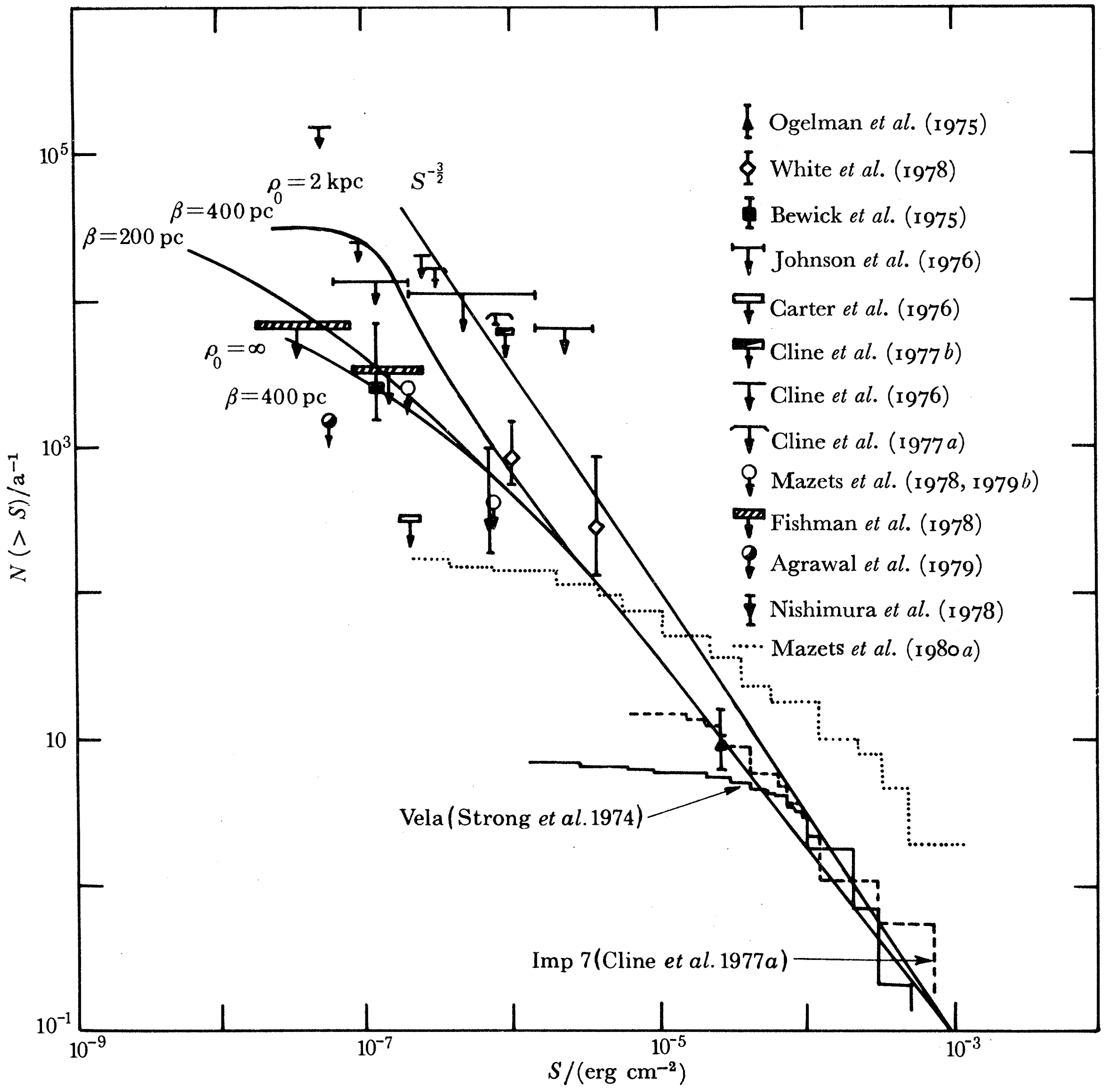

FIGURE 6. Lg N against lg S curve for γ-ray burst distribution. The different curves and their parameters are from Jennings & White (1980) and correspond to disc models with various values of distribution scale height β and with different burst rate densities given by $n(\rho) = n_{0c} \exp(\rho/\rho_0)$, where ρ is the galactocentric radius vector.

The latest results of Mazets on 143 γ-ray bursts with energies greater than 3×10^{-7} erg cm^{-2} give a lg N against lg S distribution that departs from the $S^{-\frac{3}{2}}$ law for intensities below 10^{-4} erg cm^{-2}. While this distribution agrees with the general shape of the lg N against lg S curve, it should be noted that in the region $2\times10^{-5} < S < 2\times10^{-4}$, it is at least a factor of three above the curves corresponding to the Vela and Imp 7 results. Also it is noted that the latest spatial distribution of these events does not show a clustering tendency in the galactic plane (Mazets *et al.* 1980*a*). To explain the difference between this source distribution and the lg N against lg S curve, Mazets *et al.* no longer consider the total energy of the burst as constant, but rather its average power P, that is the total intensity S divided by the duration. Thus the lg N against lg P curve has a $P^{-\frac{3}{2}}$ dependence, and the discrepancy between this curve and the spatial distribution of γ-ray bursts is eliminated. In view of the complexity of the interpretation of this lg N against lg S curve, it is very important to be able to localize as many γ-ray bursts as possible.

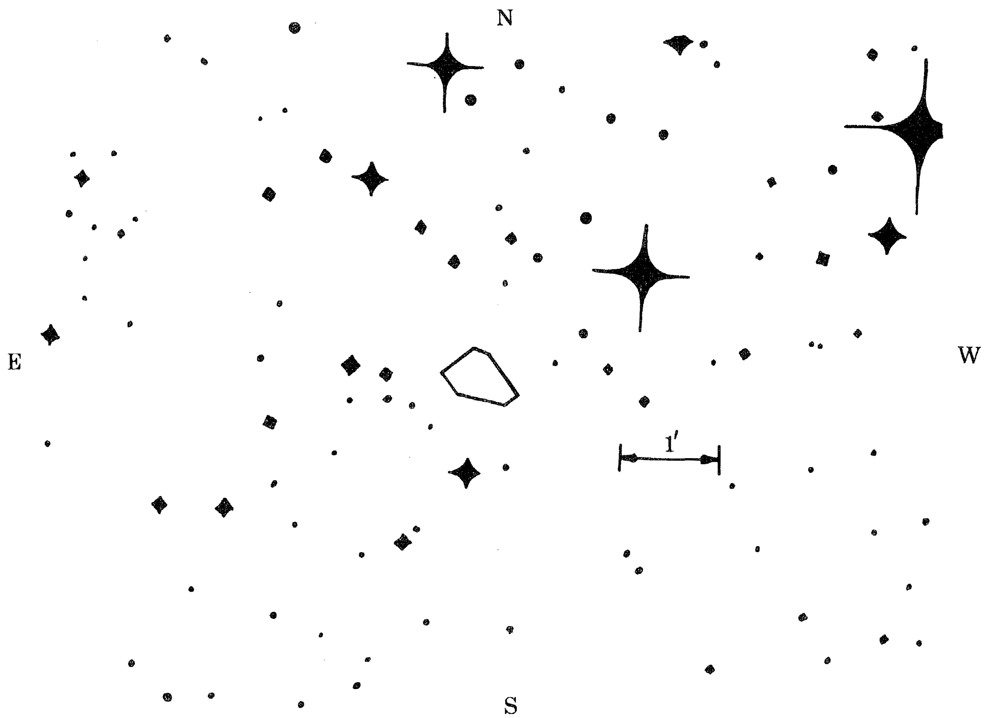

FIGURE 7. Sky map of the localized region for the April 6, 1979 event (sketch from photograph) (Lazos *et al.* 1980).

2. LOCATION

March 5, 1979

The features of this event have already been given (Cline 1980): short duration (120 ms), very fast rise time to maximum intensity, periodicity and a γ-ray line at 420 keV. At least nine spacecraft participated in the location of this event, and this was extremely precise because the distances between Helios-2, Venera 11 and 12, and Pioneer Venus Orbiter were large and because the onset of the event was particularly sharp. A first error box has already been published (Evans *et al.* 1979*a*, *b*; Vedrenne *et al.* 1980; Evans *et al.* 1980) but a later location gives an area of about $6'' \times 30''$ inside the first box and still inside the supernova remnant N 49 in the large Magellanic Cloud. Since this location is defined by a large number of experiments it is redundantly determined and this clearly adds great confidence to it or any other error boxes redundantly determined by the same spacecraft. The distance of this object, 55 kpc, and its measured flux, 2×10^{-3} erg cm^{-2} s^{-1}, imply a luminosity of about 3×10^{44} erg s^{-1}, which is

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typically five to six orders of magnitude larger than the energy contained in a burst of galactic origin. For this reason many authors have concluded that the source must be galactic and only a few hundred parsecs distant (Mazets *et al.* 1979*b*; Helfand & Long 1979; Agaronyan & Ozernoy 1979). Nevertheless, Ramaty *et al.* (1980*a, b*) can explain this large luminosity by the possibility of a vibrating neutron star with production of γ-rays by e^+–e^- synchrotron cooling and annihilation.

The burst location region was observed both before and after the burst by the Einstein Observatory (Helfand & Long 1979), and a flux variation of only $0.8\,\{^{+2.9}_{-0.8}\}\,\%$ was found in N 49. It should also be noted that the eight second periodicity observed seems too long for a young (less than 10^4 years) neutron star in N 49 (Barat *et al.* 1979). Optical observations of the N 49 region will soon be made by S. Ilovaisky and coworkers and may shed some light on these problems.

April 6, 1979

This event, observed by five instruments aboard Pioneer Venus Orbiter, Venera 11 and 12, Prognoz 7, and ISEE-C, consists of a single peak of 0.2 s duration: the spectrum, obtained from Prognoz 7, is very hard and much harder than the March 5, 1979 event, and therefore more typical of a γ-ray burst. The error box determination is given in figure 7. The diameter of this box is less than 1′, and is centred at about α_{1950} = 23h11 δ_{1950} = −49° 55′. A precise location is given by Laros *et al.* (1980).

A U.K. Schmidt plate of the region reveals no objects within the error box to m_v = 22.5 nor are there any known X- or γ-ray sources. A more recent observation by the Einstein Observatory seems to give no indication of the presence of an X-ray source in the error box. Optical observations will also be made of this region at the European Southern Observatory.

November 19, 1979

This event was observed by Helios 2, Pioneer Venus Orbiter, Venera 11 and 12, Prognoz 7, ISEE-C, and the Vela satellites (Cline *et al.* 1980*b*). It is another example of an event that can be localized with great redundancy; six high accuracy spacecraft measurements were used to give 15 rings of source location, each of thickness governed by the estimated timing errors, generally in the 30 ms region for this event, which are due to the inaccuracies of wavefront comparison. The error box (figure 8) is centred at about 19° right ascension and −29° declination (Zenchenko *et al.* 1980). It corresponds to a galactic latitude of −84°, i.e. a region where the star density is low and the obscuration negligible. This region contains no known X-ray emitter (Cline *et al.* 1980*b*), although a very weak X-ray emission seems to have been observed near the centre of the error box by the Einstein Observatory, and this appears to be consistent with the emission of a very weak radio source. In addition, two of three radio sources of a triplet have been observed by Hjellming in the error box. Three unidentified optical objects at the limit of the ESO Sky Survey plates ($m_v \approx 22$) are also in the central region of the error box. The γ-ray burst is situated near the direction of the south galactic pole and since the scale height of early galactic stars is about 100 pc or less, early stars within the Galaxy would have apparent magnitudes less than 18. As nothing is observed at this level, it excludes early stars, either isolated or in binary systems (Fishman & Duthie 1980). Recall, too, that this event shows two spectral features at 413 and 740 keV, and that it is one of the events showing the greatest spectral variability.

Other events

The November 4, 1979 event, long, highly structured and showing considerable variability in its spectrum between the start and the end of the event, has been localized to a region of about 3′ × 18′ centred at 20h06 right ascension, −21° 40′ declination. The April 18, 1979 burst has also been localized recently, in addition to five other events (November 24, 1978;

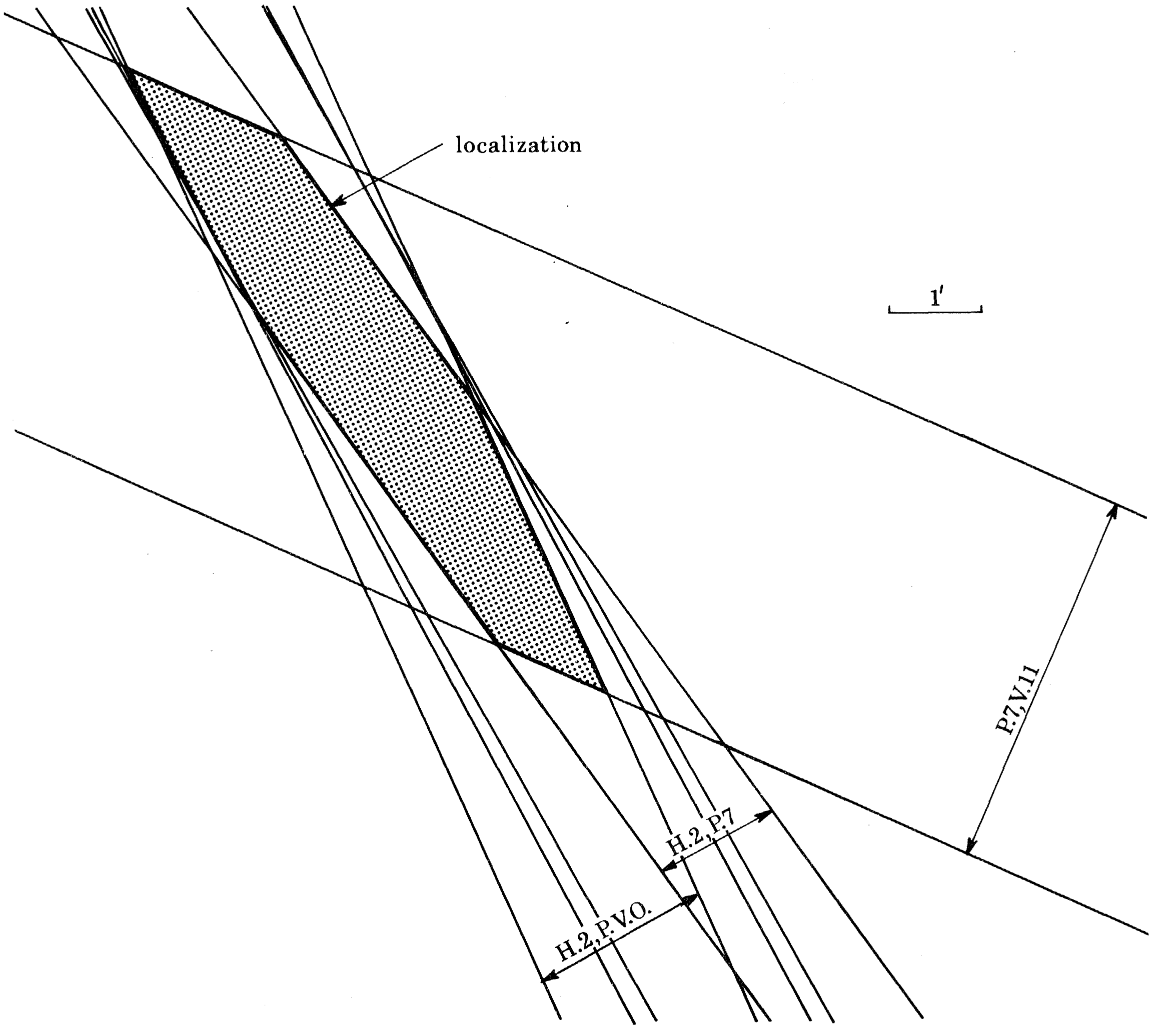

FIGURE 8. Location of November 19, 1978 event. Abbreviations: H.2, Helios 2; P.7, Prognoz 7; P.V.O., Pioneer Venus Orbiter; V.11, Venera 11. (Cline *et al.* 1980*b*.)

January 13, 1979; March 7, 1979, March 31, 1979; June 13, 1979). About six more events can be localized in the near future with an accuracy of about 0.5°. The above is the situation for bursts detected during the period September 1978 to June 1979.

To appreciate the progress in this field it must be recalled that only ten events were crudely localized in 1974, 16 in 1975 (Klebesadel & Strong 1976) and 24 in 1979 (Hurley 1980). The error box of the best localized event was 1 square degree (Cline *et al.* 1979*a*, *b*). If the new localized events are added to the sky map already given by Hurley (1980) the burst distribution

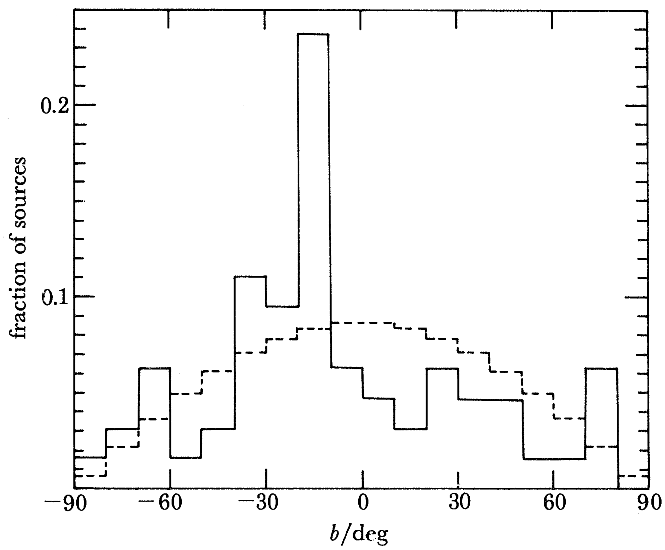

FIGURE 9. Distribution of 63 located sources against b, compared with an isotropic distribution ($0° \leqslant l \leqslant 360°$). Of the 63 sources, 50 were taken from the Mazets's catalogue (Mazets *et al.* 1979*d*, *e*, 1980*c*) for the period September 1978 to October 1979. ——, Distribution of 63 sources; – – –, isotropic distribution.

does not give any concentration of sources in the galactic centre region. Even Mazets *et al.* (1980*a*), reporting on their latest results obtained on 59 sources, conclude that the γ-burst source distribution is isotropic. However, if we look at the galactic distribution of 63 located bursts (50 located by Mazets) we notice a significant concentration in the south galactic hemisphere (42, compared with 21 in the north galactic hemisphere) with a clear excess in the region $-30° < b < 0°$ and especially around $b = -15°$ (figure 9). This kind of anisotropy has not been reported previously, perhaps because, in general, bursts are plotted against $|b|$ between 0° and 90°. If we take independently the distribution of more than 20 located γ-ray bursts, some of them already reported by Hurley (1980) and others obtained more recently by the international network (a catalogue of these events is in preparation), this effect is much less significant, but the statistic is lower. We see no way to explain this anisotropy by some instrumental effect.

3. Some implications of the more recent results

First, the theoretically calculated lg N against lg S curve as well as the most recent observational results, especially those obtained from very large area balloon detectors, definitely show that a lg N against lg S curve with an exponent of $-\frac{3}{2}$ is not acceptable for all the observations. For fluxes below 10^{-5} erg cm^{-2} the slope approaches s^{-1}, which implies a disc distribution. The most recent comparison between experimental and theoretical results excludes a central source concentration and suggests a disc distribution with a thickness of 400 parsec (Jennings & White 1980). However, it must be remarked that the galactic distribution of γ-ray bursts given by Mazets *et al.* (1980*b*), does not show any evidence of a concentration in the disc. This is still true even if only the faintest sources observed by Mazets ($S < 5 \times 10^{-5}$ erg cm^{-2}) are taken into account. It is possible that the strange galactic distribution against b of figure 9 is connected with the eccentric position of the Sun with respect to the galactic disc. If this effect is confirmed it favours a local origin for almost all the bursts already located. This question must be studied in more detail.

Other considerations connected with the bursts rates and their probable galactic origin have led to the conclusion that the burst source population must have a certain event repetition rate, which, of course, depends strongly on whether the emission is isotropic or beamed. Note that besides the lg N against lg S curve the fact that there are photons of energy above 1 MeV in γ-ray burst sources seems to exclude extragalactic models for most of them. The presence of very fine time structure in many events favours emission by compact objects. Moreover the presence of lines for some events with redshifts compatible with 1 $M_{\odot}$ objects leads to the same conclusion. If confirmed, the presence of the cyclotron line recently reported would likewise favour a compact-object origin. Finally, the variability of some events (e.g. the November 19, 1978 burst) recalls the Comptonization phenomenon discussed by Sunya'ev *et al.* (1979) for Cyg X–1, even though some events, such as April 29, 1972, are well explained by bremsstrahlung emission from an optically thin region. If compact objects are confirmed as the sources of γ-ray bursts, the two emission processes that should be kept in mind are instability phenomena in the interior of the star, starquakes (Bisnovatyi-Kogan & Chechetkin 1980*a*, *b*; Fabian *et al.* 1976) and thermonuclear flashes (Woosley & Taam 1976).

In summary, to understand better the origin of these emissions, a coordinated observation programme with several satellites separated by large distances must be maintained. The International Solar Polar Mission will offer a unique opportunity to localize many γ-ray bursts with accuracies up to about 10″ over a long period. Given the large diversity in the temporal and spectral characteristics of the γ-ray bursts detected to date, it is quite possible that several classes of objects are responsible, just as for X-ray sources. The presence of lines in certain events constitutes a very strong argument for including high energy resolution detectors, covering the energy range from kiloelectronvolts to megaelectronvolts on future missions; the presence of cyclotron or nuclear lines is a unique feature which invites a better understanding of emitting objects and emission conditions. The Gamma Ray Spectroscopy Expriment and the Fishman experiment aboard the Gamma Ray Observatory satellite are therefore important elements in the international network which will include the two I.S.P.M. spacecraft. The S.M.M. experiments of Frost and Chupp and the HEAO-C experiment of Jacobson, which are currently in orbit, may be able to add considerably to our knowledge of γ-ray bursts, and especially to our understanding of spectra and possible line features.

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