letters

Observations of a flaring X-ray pulsar in Dorado

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The γ-ray burst detector Konus[1], on the Venera 11 and Venera 12 spacecraft, detected on 5 and 6 March, 1979 two bursts of hard X rays originating from the same source. These events are quite unusual and of considerable interest. The burst of 5 March was very intense, particularly in the initial phase. This event was also observed by several other spacecraft[2]. The second burst on 6 March was considerably weaker. The observations reported here permitted us to obtain a detailed time structure of the bursts, to measure their energy spectra and to locate the source on the celestial sphere.

Figure 1 displays the time structure of the initial phase of the 5 March burst recorded on Venera 11 in the energy range 50–150 keV with a time resolution of 1/64 s. Note that all results obtained on Venera 11 and Venera 12 coincide completely. The burst has a very sharp onset. The initial, narrow structureless pulse is characterised by a very short rise time, ~15 ms, and a longer decay, ~150 ms. The peak count rate in the 50 cm^2 sensor attains 4×10^5 c.p.s. This means that during a short time (~0.1 s), the flux of hard X rays exceeded the diffuse cosmic background by a factor of 10^4. The time structure of the burst measured with resolutions of 1/4 and 1 s is shown in Fig. 2*a*, *b*. An analysis of these data clearly indicates that the radiation observed is that of an X-ray pulsar with a period 8.1 ± 0.1 s (ref. 3). The pulsed radiation is seen to exhibit a train of stronger pulses and another train of interpulses with a relative phase of 0.5. The level of intensity in the deep minima between the pulses apparently reflects a slowly varying component of radiation.

The most remarkable fact here is that the onset of radiation is almost instantaneous with a subsequent fast decay. The standard length of measurements (66 s) was found to be insufficient for this event; however, measurements carried out 6 min after the beginning of the burst revealed that by this time the intensity of radiation had decreased to background level.

Eight consecutive measurements of the energy spectra were carried out, each of 4 s duration. Only the first spectrum measured in the initial burst phase differs in shape from the others. Therefore, Fig. 3 presents the energy spectrum of the burst for the first time interval, 0–4 s (histogram *a*), and a spectrum averaged over the interval 4–32 s (histogram *b*). The energy spectra of this event differ from those of most of the γ-bursts[4]. The shape of the pulsed radiation spectrum is more similar to those of the spectra of continuously emitting X-ray sources, such as Cyg X−1, than to the substantially harder spectra of typical γ bursts. It may be approximated by the relationship $E^{-1}\exp(-E/kT)$, with $kT=30$ keV.

The spectrum of the initial burst phase has a harder tail, which is possibly associated with radiation of only the initial pulse. The spectral feature in the region 400–500 keV is a remarkable characteristic of this spectrum. The total identity of the spectra obtained on Venera 11 and Venera 12 completely eliminates the possibility that this feature is a result of random fluctuations. A more detailed analysis of the spectrum shows that the observed feature may be associated with the presence of a broad line at 430 keV with a FWHM of 30–40%. It is difficult to suggest an unambiguous explanation of the nature of this radiation component. Note, however, that 430 keV corresponds to the energy of the 511-keV annihilation line which has undergone a redshift of $(1-2GM/c^2R)^{1/2}$ in the gravitational field of a compact object with $M=1M_\odot$ and $R=10^6$ cm.

The average pulsed radiation flux with $E_\gamma>30$ keV is 1×10^{-5} erg cm^{-2} s^{-1}. At the peak of the initial pulse the flux is 1.5×10^{-3} erg cm^{-2} s^{-1}. Evaluation of the flux in the line with $E_\gamma\approx430$ keV yields 3×10^{-6} erg cm^{-2} s^{-1}, or, assuming the line radiation to be emitted only in the initial pulse, 5×10^{-5} erg cm^{-2} s^{-1}.

The location of this flaring X-ray pulsar, designated earlier FXP 0520−66 (ref. 3), is shown in Fig. 4. The readings of the Konus sensor unit with anisotropic angular sensitivity yield a fairly large error box with sides of about 3°. Intersection of this region with a narrow annulus obtained from the time-of-arrival difference between Venera 11 and Venera 12 gives the final box as a narrow annular band 4′ wide. Based on the latest spacecraft trajectory data, the position of this annulus on the celestial sphere is defined by the angular radius $68.528\pm0.030°$ with the centre at $\alpha=44.427°$, $\delta=-2.747°$ (1950.0). This position is in good agreement with other data. The arc of radius 68.528° passes 1.7 arc min to the south-east of the centre of the error box for this source given in ref. 2 — $\alpha=5$ h 25.92 min, $\delta=-66.122°$.

As mentioned above, the observed source was found to be recurrent. On the next day, 6 March, the Konus detector on both spacecraft recorded, after the same time interval $\Delta t=$ 14 h 25 min 46.15 s a short burst ~1.5 s long with the same soft

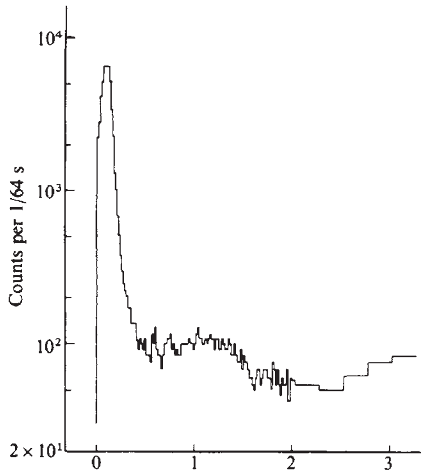

Fig. 1 Initial stage of the 5 March event as recorded on Venera 11. The data of Venera 12 are identical. Energy range covered 50–150 keV. Time resolution, 1/64 s. Burst onset time t_0. Venera 11: 15 h 51 min 39 s, 145 UT. Venera 12: 15 h 51 min 44 s, 350 UT.

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spectrum (Fig. 3, histogram *c*). Its intensity, however, was 100 times lower. Its time structure is shown in Fig. 2*c*, *d*, with results of source location determination presented in Fig. 4. For the 6 March event, the process responsible for the emission in the source was evidently weaker and longer than in the case of the 5 March burst. We can assume that the decaying pulsed radiation could have been accordingly weaker and, hence, not observable against the background present.

The most plausible model for the FXP0520 − 66 source seems to be a binary system containing a neutron star. The separation between the components should be sufficiently large to reduce the accretion rate to the level where there would be no observable radiation in the steady state. The neutron star should possess a strong magnetic field; indeed, the presence of two pulse trains in the burst implies that during accretion the plasma moves along the field lines with the emitting regions located near the magnetic poles. The origin of the non-stationary accretion resulting in a burst remains unclear. The characteristic rise time to almost full peak luminosity is small, less than 15 ms, implying that processes associated with the neutron star proper, such as the development of instabilities in the magnetosphere, should play the part of the trigger mechanism.

The observed source projects on to the Large Magellanic Cloud. Moreover, it lies close in position to the supernova remnant N49 in the Large Magellanic Cloud[2]. However, its energetics suggest that it is not only located in our Galaxy, but even comparatively close to the Sun. Indeed, if the source were at 55 kpc the luminosity of isotropic radiation in the initial impulse would be $\sim 5\times10^{44}$ erg s^{-1}, and that at the pulsating stage, $\sim 3.6\times10^{42}$ erg s^{-1}. Accordingly, the energy released in the initial impulse would be $\sim 1.2\times10^{44}$ erg, that at pulsating stage (lasting ~100 s) $\sim 3.6\times10^{44}$ erg, and in line radiation, $\sim 10^{42}$ erg. The total energy in the event would then be $>4.6\times 10^{44}$ erg. The shape of pulsations (Fig. 2) shows that the angular pattern of emission cannot be very narrow. Taking into account possible directivity of emission could not reduce these estimates by more than a factor of 10. Such large figures for the total energy and luminosity apparently rule out the possibility that this source is located in the Large Magellanic Cloud. On the other hand, if its average luminosity in the pulsating phase is close to that of X-ray sources in binaries (10^{37}–10^{38} erg s^{-1}), an estimated distance to it is 100–300 pc.

Consider some implications of the assumption on the galactic nature of this unusual X-ray pulsar. In its characteristics, mainly in the time scale of its variability and the presence of an impulsive initial stage, the FXP0520 − 66 source differs

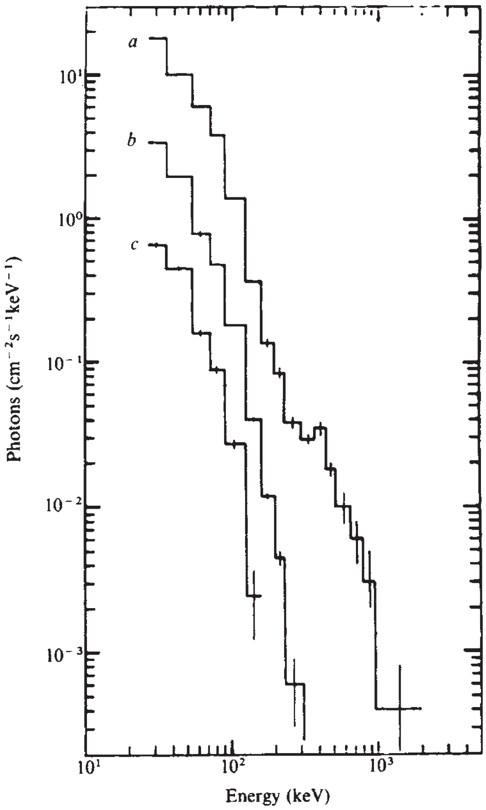

Fig. 3 Burst energy spectra. *a*, 5 March, spectrum of initial stage for the first 4 s; *b*, 5 March, averaged spectrum of pulsed radiation; *c*, spectrum of 6 March burst. Data from Venera 11 and Venera 12 are identical.

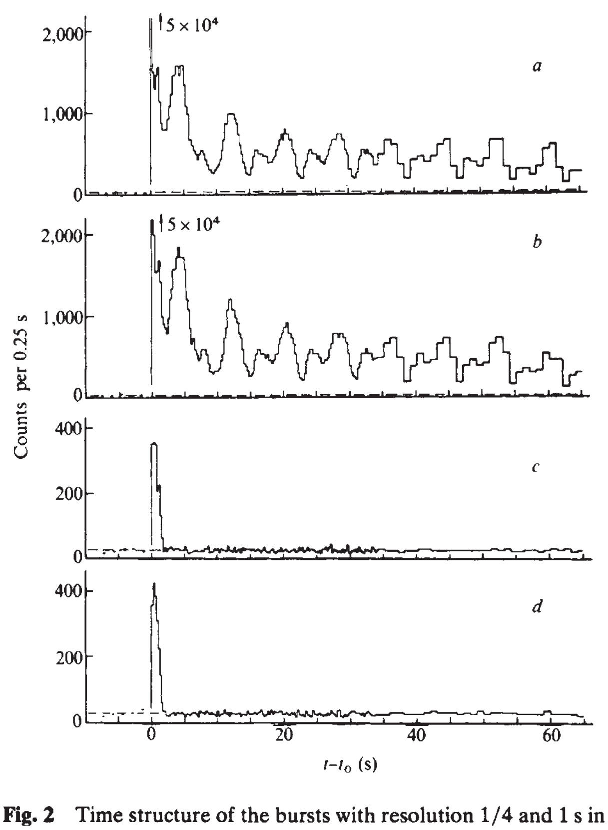

Fig. 2 Time structure of the bursts with resolution 1/4 and 1 s in the energy range 50–150 keV. *a*, 5 March, Venera 12; *b*, 5 March, Venera 11; *c*, 6 March, Venera 12: $t_0 = 6$ h 17 min 30 s, 455 UT. *d*, 6 March, Venera 11: $t_0 = 6$ h 17 min 25 s, 200 UT. Dashed line indicates background count rate. Points before t_0 show previous history of the bursts.

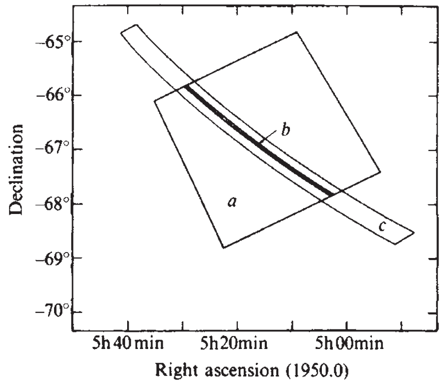

Fig. 4 Location of FXP 0520 − 66 source. Error box: *a*, for 5 March event, determined from detector anisotropic angular response; *b*, for 5 March event, obtained from detector anglular response and time-of-arrival difference; *c*, same for 6 March event.

markedly from the known transient sources[5]. It is unlikely that this source is the only one in the Galaxy. Other such sources probably exist and should be observable. However, the distances to them shoud be, on average, much larger, about a few kpc. Therefore, the observable radiation flux from such sources should be small. This implies that flaring X-ray pulsars could be detected primarily in their initial impulsive phase as short bursts of hard X-ray radiation.

Do the abovementioned differences in the spectral characteristics indicate that a binary cannot be the origin of γ-ray bursts? Apparently, not. Indeed, the revealed concentration of the γ-burst source locations in the direction of the galactic centre implies that distances to them are large and should be, on average, a few kpc (ref. 4). The corresponding estimates of the average energy released in γ-ray burst sources, 10^{40}–10^{41} erg, yield a value of 10^{39}–10^{40} erg s^{-1} for the average luminosity. These values exceed by at least 2 orders of magnitude the luminosity of known binary X-ray sources, as well as that of the FXP0520−66 source in its pulsating stage. Therefore, it is natural to suggest that the hardness and the shape of the radiation spectrum are substantially dependent on accretion rate, and it is the very high power of non-stationary accretion that determines the typically hard energy spectra of the γ-ray bursts that approach the power law in shape. The presence in the 5 March event of a hard component in the energy spectrum of the powerful initial impulse strongly supports this assumption.

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1. Mazets, E. P. *et al. Pisma astr. Zh.* **5**, 163–167 (1979).
2. Evans, W. D. *et al. IAU Circ.* No. 3356 (1979).
3. Mazets, E. P. *et al. FTI preprint* no. 617 (1979).
4. Mazets, E. P. *et al. FTI preprint* no. 618 (1979).
5. Willmore, A. P. *Rep. Progr. Phys.* **41**, 511–585 (1978).

X-ray observations of the 5 March 1979 γ-burst field

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On 5 March 1979, an extremely intense burst of hard X rays and γ rays was recorded by the nine interplanetary spacecraft of the burst sensor network and localised by time-of-flight determinations to a position coincident with the supernova remnant N49 in the Large Magellanic Cloud[1–3]. Several times, both before and after the γ-ray event, we observed this region of the sky with the soft X-ray imaging instruments aboard the Einstein Observatory. Coupled with optical plate material, the soft X-ray data are used here to place severe constraints on models for the origin of this remarkable transient phenomenon.

The γ-ray observations are reported in the preceding letter[2]. Briefly, the salient features of the event include an extremely high peak flux (1.5×10^{-3} erg (cm^2 s)$^{-1}$ above 30 keV), a rapid rise time ($\lesssim$0.25 ms, ref. 1), a decline to a flux level 10^{-2} times that of the peak within a second, followed by a slow (~100 s) decay characterised by 8.1-s pulsations, a soft γ-ray spectrum which during the initial burst shows evidence of a line feature near 430 keV, and a second much weaker burst 14 h later. The morphology, period and spectrum of the pulsed component are reminiscent of pulsating binary X-ray sources, such as Her X-1 and Cen X-3, which are thought to contain magnetised rotating neutron stars and to be powered by accretion from a normal companion star. The case for the presence of a neutron star in the system responsible for the γ-ray event is strengthened if one interprets the 430 keV emission line as redshifted electron–positron annihilation radiation. The implied gravitational field is just that found due to a $1M_\odot$ object with a radius of 10 km. The positional coincidence of the γ-ray event and a supernova remnant (SNR) might be cited as further evidence that a neutron star was involved; however, the luminosities implied by the association of this event with the Large Magellanic Cloud are quite large: $L_\gamma \sim 5\times10^{44}$ erg s^{-1} at the burst peak and $L_\gamma \sim 4\times10^{42}$ erg s^{-1} during the pulsing phase. In what follows, the X-ray data are presented and then used to set limits on possible interpretations for the origin of the event.

The X-ray observations were carried out as part of a complete soft X-ray survey of the Large Magellanic Cloud that has been underway since the beginning of the year[4]. The instrumentation of the Einstein Observatory has been described elsewhere[5]. With the imaging proportional counter (IPC) in the focal plane of the telescope, a $1°\times1°$ field of view is imaged with a spatial resolution of 1.5′ (FWHM), while the spatial resolution obtainable with the high resolution imager (HRI) over a $25'\times25'$ field is 4″. The initial IPC pointing, which occurred 8 days before the burst, revealed the presence of two bright sources of soft X-ray emission centred on N49 and (N49), emission nebulae in the Large Magellanic Cloud previously identified as SNRs[6]. With the moderate resolution of the IPC, N49 was unresolved; its companion 6′ to the north-west showed some evidence of extended structure. The results of the subsequent HRI observations are shown in Fig. 1. The source associated with (N49) is seen to be a uniform, symmetric emission region with a diameter of ~40 pc. By contrast, N49 is ~25 pc in diameter with a strong enhancement in the south-east quadrant and bright knots of emission similar to those observed by Dopita and Mathewson[7] and D. Clark (personal communication) in recent maps of coronal [Fe XIV] emission. A detailed discussion of the X-ray structure of SNR in the Large Magellanic Cloud will be given elsewhere. Here, we concentrate on those aspects of the data relevant to the 5 March event.

Our first important constraint on models for the γ-ray burst derives from the constancy of the flux from the N49 region in the two IPC observations carried out 0.72×10^6 s before and 3.29×10^6 s after the γ-ray event. We can quantify this constancy, independent of instrumental or background effects, by taking the ratio of the flux in the region of N49 to that from (N49). These ratios in the two IPC images are 2.167 ± 0.09 and 2.185 ± 0.09, corresponding to a limit on the change in flux from N49 of $<0.8\%^{+2.9\%}_{-0.8\%}$. Assuming a power law spectral index of −2 and a low energy cutoff of 0.5 keV, this corresponds to a 3σ upper limit on the change in flux of 2.2×10^{-12} erg (cm^2 s)$^{-1}$.

The improved spatial resolution of the HRI permits us to derive a second result—namely, a limit on the strength of any point source within the instrument's $25'\times25'$ field of view. This limit is obtained by summing the number of counts detected in $8''\times8''$ regions of the map and then subtracting a local background counting rate determined from the eight adjacent regions. The limits thus obtained depend on the mean surface brightness of the area being searched. For the region of extended emission within N49, the 3σ upper limit is 9.9×10^{-3} c.p.s., whereas for the area outside N49 but still near the γ-ray error box, the limit is $\sim10^{-3}$ c.p.s. These point source limits correspond respectively to flux limits of 2.1×10^{-12} erg (cm^2 s)$^{-1}$ and 2.2×10^{-13} erg (cm^2 s)$^{-1}$ (0.5–4.5 keV). The greater of these two values is therefore essentially the same as the limit to any change in flux derived from the IPC.

These X-ray limits imply that, independent of distance, the steady-state (or remnant) luminosity from the system which produced the γ-ray event is less than 10^{-9} that observed above 30 keV in the burst. This translates to a luminosity limit of $2\times10^{30}\ d_{100}^2$ erg s^{-1}, where d_{100} is the distance to the source in units of 100 pc. At the Large Magellanic Cloud, the limit on L_x is $<4\times10^{35}$ erg s^{-1}, two orders of magnitude smaller than that of a typical pulsating binary X-ray source.

In Table 1, we present these limits along with the γ-ray luminosities and energies and a variety of model-dependent

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