

The Konus-Wind and Helicon-Coronas-F detection of the giant γ -ray flare from the soft γ -ray repeater SGR 1806-20

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ABSTRACT

The giant outburst from SGR 1806-20 was observed on 2004 December 27 by many spacecraft (ref. 1,2,3,4,5,6). This extremely rare event exhibits a striking similarity to the two giant outbursts thus far observed, on 1979 March 5 from SGR 0526-66 (ref. 7) and 1998 August 27 from SGR 1900+14 (ref. 8,9,10). All the three outbursts start with a short giant radiation pulse followed by a weaker tail. The tail pulsates with the period of neutron star rotation of $\sim 5-8$ s, to decay finally in a few minutes. The enormous intensity of the initial pulse proved to be far above the saturation level of the gamma-ray detectors, with the result that the most valuable data on the time structure and energy spectrum of the pulse is lost. At the time of the December 27 outburst, a Russian spacecraft Coronas-F with a γ -ray spectrometer aboard was occulted by the Earth and could not see the outburst. It succeeded, however, in observing a weak reflected signal due to the γ -rays Compton scattered by the Moon (ref. 11). This has been the first observation of a cosmic gamma-ray flare reflected from a celestial body. Here we report, that the detection of a weakened back-scattered initial pulse combined with direct observations by the Konus γ -ray spectrometer on the Wind spacecraft permitted us to reliably reconstruct the intensity, time history, and energy spectra of the outburst.

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During the period elapsed since its launch in 1994, Konus-Wind has detected three giant outbursts. The first of them came on 1998 June 18 from SGR 1627-41 (ref. 12). It was weaker than the others and did not have a pulsating tail. The second giant outburst, on 1998 August 27 (ref. 8,9,10), was associated with SGR 1900+14. It is to this event that the giant outburst on 2004 December 27 from SGR 1806-20 is very similar.

On Wind, the record of this outburst was triggered by a preceding recurrent soft burst at $T_0=21:27:58.447$ s UT. This burst was the last but strongest of a series of 10 recurrent bursts which occurred on December 27 before the giant outburst. The strongly enhanced SGR recurrent activity at the end of 2004 could be an indication of an approaching giant outburst, as was the case with the 1998 August 27 event (ref. 13). Figure 1 presents a fragment of the time history of the giant outburst recorded with a 0.256-s resolution. The event started at $T - T_0=142.08$ s with an extremely steep intensity rise to drive the gamma detector far above the saturation level for ~ 0.5 s. On termination of the initial pulse and with the detector having resumed operation, the burst tail became visible until its decay after ~ 380 s. The burst tail intensity pulsates with the period of neutron star rotation $P = 7.57 \pm 0.07$ s. Each period exhibits a complex, three-peaked pulsation structure. The count rate ratio of the G2 (65–280 keV) to G1 (16.5–65 keV) energy windows is a measure of the spectral hardness of the radiation. Within each period, the spectral hardness correlates with the intensity structure. Most likely the variations in the intensity and spectral shape during a period are caused by changing of the viewing angle on a rotating anisotropic source. Figure 2 displays an energy spectrum of the tail averaged over the pulsation period. The spectrum consists of two components, with the energy region of up to $\simeq 400$ keV being dominated by a component falling off exponentially with energy, and at energies > 400 keV by a power law with a photon index of -1.8 ± 0.2 . Such spectra vary very little in shape as the burst decays. Each of them contains a weak hard power-law component extending to as far as 10 MeV. The total fluence in the outburst tail can be estimated as 1.2×10^{-2} erg cm^{-2} in the 20 keV–10 MeV band. Estimation of the initial pulse fluence from complete detector saturation during ≈ 0.5 s can yield only its lower limit $> 10^{-2}$ erg cm^{-2} . Thus, direct observation of an outburst does not permit one to obtain data on the intensity, time history, and energy spectrum of the initial pulse.

A fortunate chance to gain this information has been provided by observation by the Helicon instrument on Coronas-F of a short gamma-ray burst on 2004 December 27 at 21:30:29.303 s UT. Figure 3 presents a time history of this burst recorded in the energy windows G1 (25–100 keV) and G2 (100–450 keV), and the G2/G1 ratio which exhibits a strong hard-to-soft spectral evolution. Shown in Fig. 4 is an average energy spectrum accumulated over 128 ms after T_0 . There are two grounds arguing for this burst to result from Compton scattering of the giant pulse by the Moon. First, it is consistent with the

delay of its arrival to Coronas-F and Wind to be expected in this case (a schematic diagram of the flare wavefront propagation is shown on Fig. 5). Second, while the shape of the measured energy spectrum is far from typical of gamma-ray bursts, it fits quite well the so-called Compton backscattering peak at scattering angles of about 180° , where the energy of singly scattered photons cannot exceed $\sim mc^2/2$. The real angle through which the radiation incident on the Coronas-F detector was scattered lies in the range $159.5\text{--}159.9^\circ$. The right-hand wing of the observed spectrum derives primarily from scattering, multiple as well as single, of photons with energies in excess of ~ 200 keV striking the Moon. In this energy region, the cross section of photoabsorption is substantially lower than that of Compton scattering. The left-hand wing covers a low energy region where photoabsorption becomes strongly dominating over scattering, so that an ever decreasing fraction of photons is capable of escaping out of the lunar soil.

To determine the spectrum and intensity of the initial pulse, the burst radiation scattering from the Moon was numerically simulated by the Monte Carlo method using the well-known GEANT code developed in CERN (ref. 14). A response matrix of the Moon for the above-mentioned scattering angles was calculated for a broad photon energy range from 20 keV to 12 MeV and folded then with the detector response matrix. The result of the spectrum simulation is also shown in Fig. 4. The best-fit model was found to be a power law function with an exponential cutoff, $dN/dE = A(E/100)^\alpha \exp(-E/E_0)$ with $\alpha = -0.7$ and $E_0 = 800$ keV. The reflected energy flux seen by Coronas-F is weak being attenuated by a factor of $\approx 10^{-6}$. The energy spectrum statistics is poor, particularly in the wings. Therefore, the confidence regions of 68 and 90% for the α and E_0 parameters shown in Fig. 6 are fairly large. One readily sees, however, that the fitting parameters α and E_0 are in strong anticorrelation. As a result, the estimates of the total energy in the pulse vary rather weakly. At a confidence level of 90% the fluence and the peak flux of the initial pulse in the 20 keV–10 MeV energy band are $0.61^{+0.35}_{-0.17}$ erg cm^{-2} and $9.2^{+5.6}_{-3.1}$ erg cm^{-2} s^{-1} .

Photons scattered from different zones of a spherical target reach an observer with a relative time delay whose maximum value is $2R_M/c = 11.6$ ms, where R_M is the Moon's radius, and c is the velocity of light. This gives rise to a blurred time profile of the reflected signal (Fig. 3). Correspondingly, the real front of the initial pulse should be shorter than observed, $\approx 10\text{--}15$ ms. Figure 7 displays a reconstructed time profile of the initial pulse. By Wind's information, the giant outburst starts with a comparatively slow intensity rise, which transforms in ~ 20 ms to an avalanche-type growth. The continuation of the time history was derived from Coronas-F data by introducing the corresponding corrections for attenuation and spreading of the signal as it is scattered and propagates to Coronas-F. As evident from the figure, the intensity reaches a peak of $\sim 10^7$ photons cm^{-2} s^{-1} . At Helicon sensitivity, the initial pulse is detected over a background for ~ 150 ms. A saturation of the Konus lasts

longer, about 600 ms.

Assuming isotropic emission and a distance to SGR 1806-20 of 15 kpc (ref. 15), the energy release and the maximal luminosity of the initial pulse are 1.6×10^{46} erg and 2.5×10^{47} erg s⁻¹. The energy release in the tail of all the three giant outbursts in the SGRs is $\sim 10^{44}$ erg, and one may expect the energy confined in their initial pulses to be comparable, about $\sim 10^{45} - 10^{46}$ erg. This is consistent with our earlier assumption that the lower limit on the energy released in the initial pulse of the giant outbursts from SGR 1900+14 is actually many times smaller than its true value (ref. 9), because the referred value of $> 7 \times 10^{43}$ erg was calculated for a minimum flux which is capable of saturating the Konus. The energy release of 10^{46} erg is comparable to the energy stored in the magnetosphere of a neutron star with a surface magnetic dipole field of $\sim 10^{14}$ G. This may present serious difficulties for the magnetar model of SGRs (ref. 16). Giant outbursts from SGRs at larger distances should be observed as short (~ 0.25 s) gamma-ray bursts with a hard spectrum (ref. 17). It is conceivable that it is such events that make up part of the Konus-Wind catalog of short gamma-ray bursts (ref. 18). Present-day gamma-ray spectrometers, which can reliably measure the time profile and energy spectrum of short gamma-ray bursts with fluences of $\sim 10^{-7}$ erg cm⁻², should be capable of recording the initial pulses of giant outbursts from SGRs at distances of ~ 30 Mpc. If such a burst is localized to within $\sim 5-10$ arc minutes, its identification with a host galaxy may become possible.

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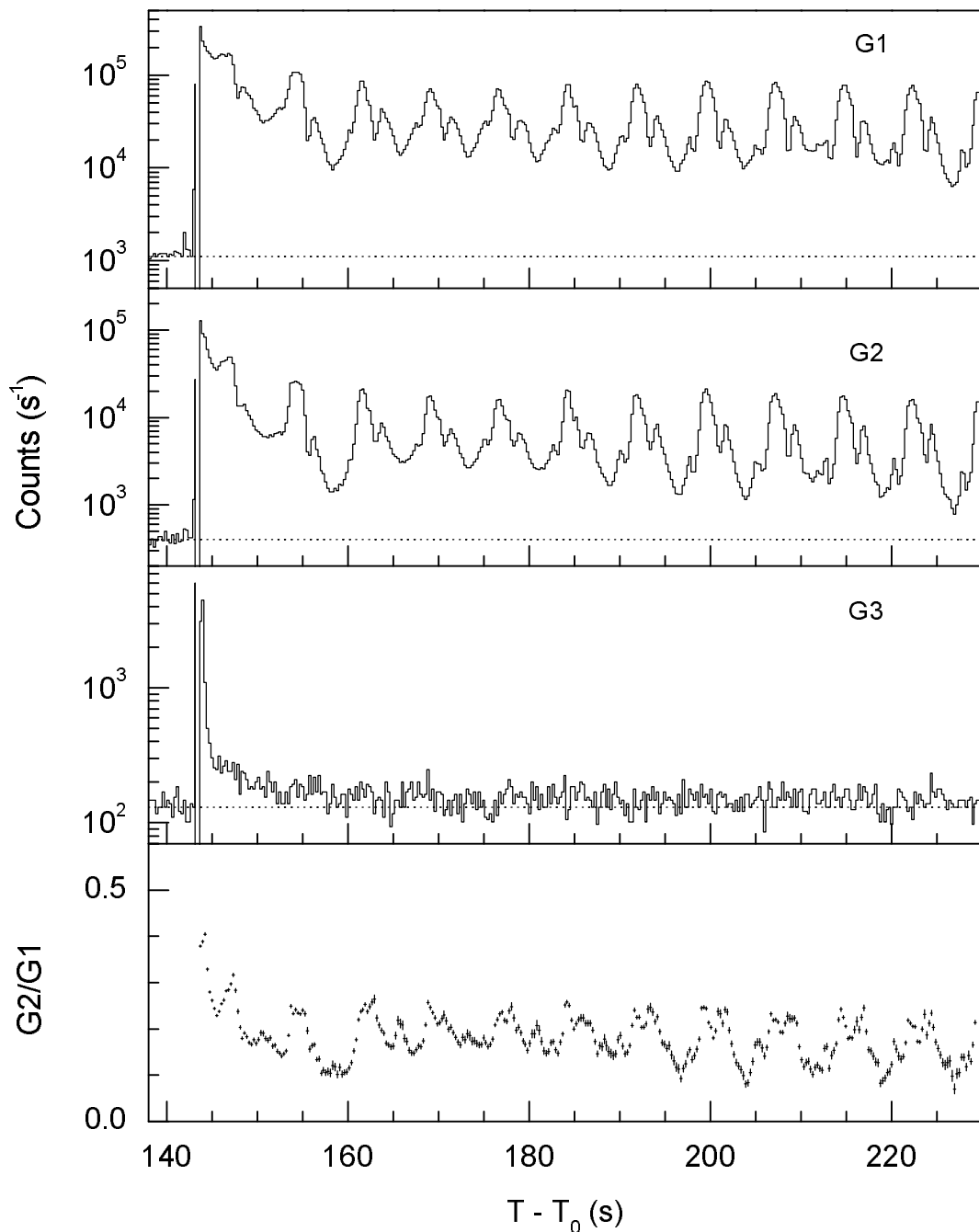


Fig. 1.— Time history of the 2004 December 27 giant outburst recorded by the Konus-Wind detector in three energy windows G1 (16.5–65 keV), G2 (65–280 keV), and G3 (280–1060 keV), and the hardness ratio $G2/G1$. The moderate initial count rate growth to 10^2 – 10^3 counts s^{-1} transforms rapidly to an avalanche-type rise to levels $> 5 \times 10^7$ counts s^{-1} , which drives the detector to deep saturation for a time $\Delta T \simeq 0.5$ s. After the initial pulse intensity has dropped to $\sim 10^6$ counts s^{-1} , the detector resumes operation to record the burst tail.

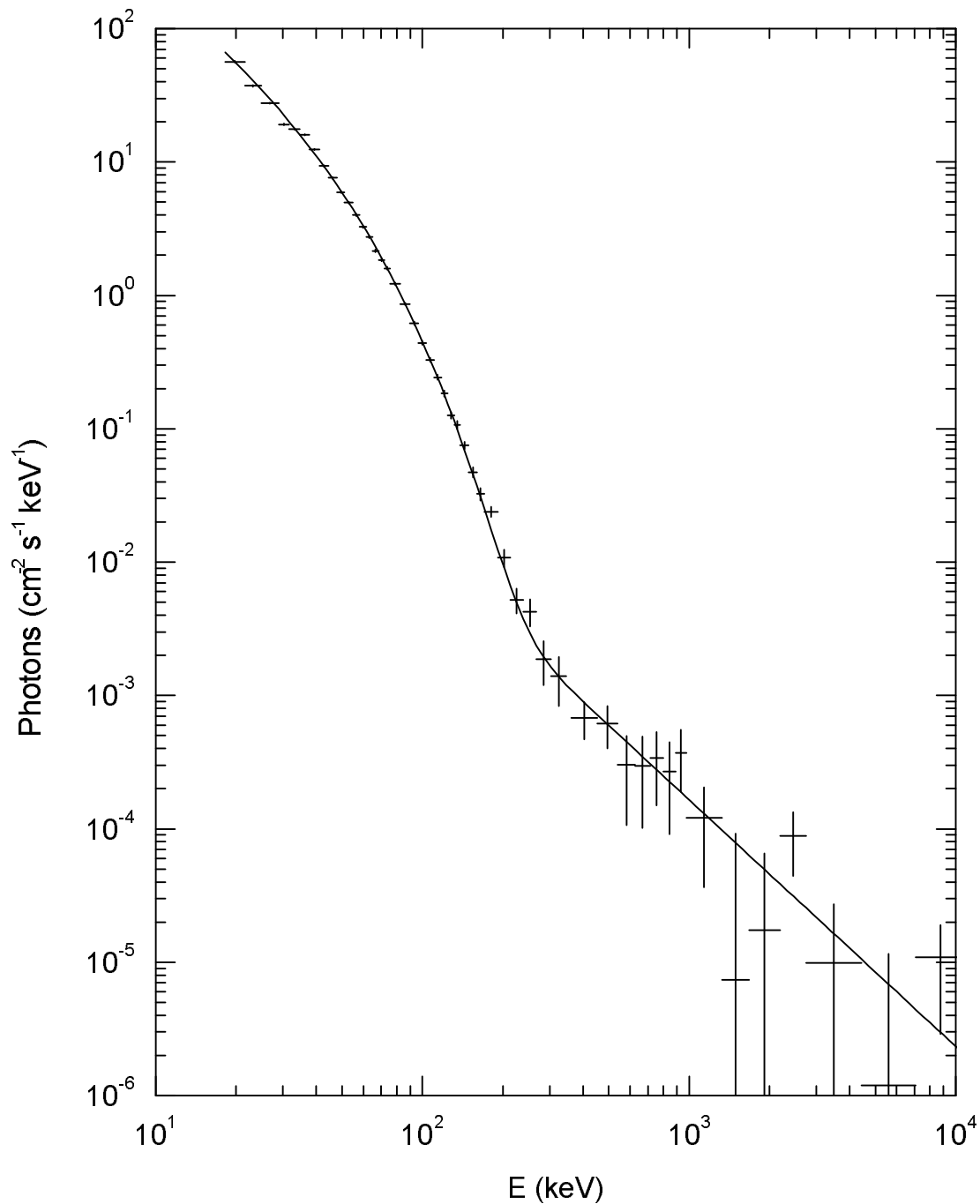


Fig. 2.— A spectrum of the burst tail averaged over the pulsation period. The low-energy component is similar to spectra of SGR's recurrent bursts with $E_0 \simeq 30$ keV. At high energies it exhibits a hard power-law component with $\alpha = -1.8 \pm 0.2$. This two-component model is shown by the solid line.

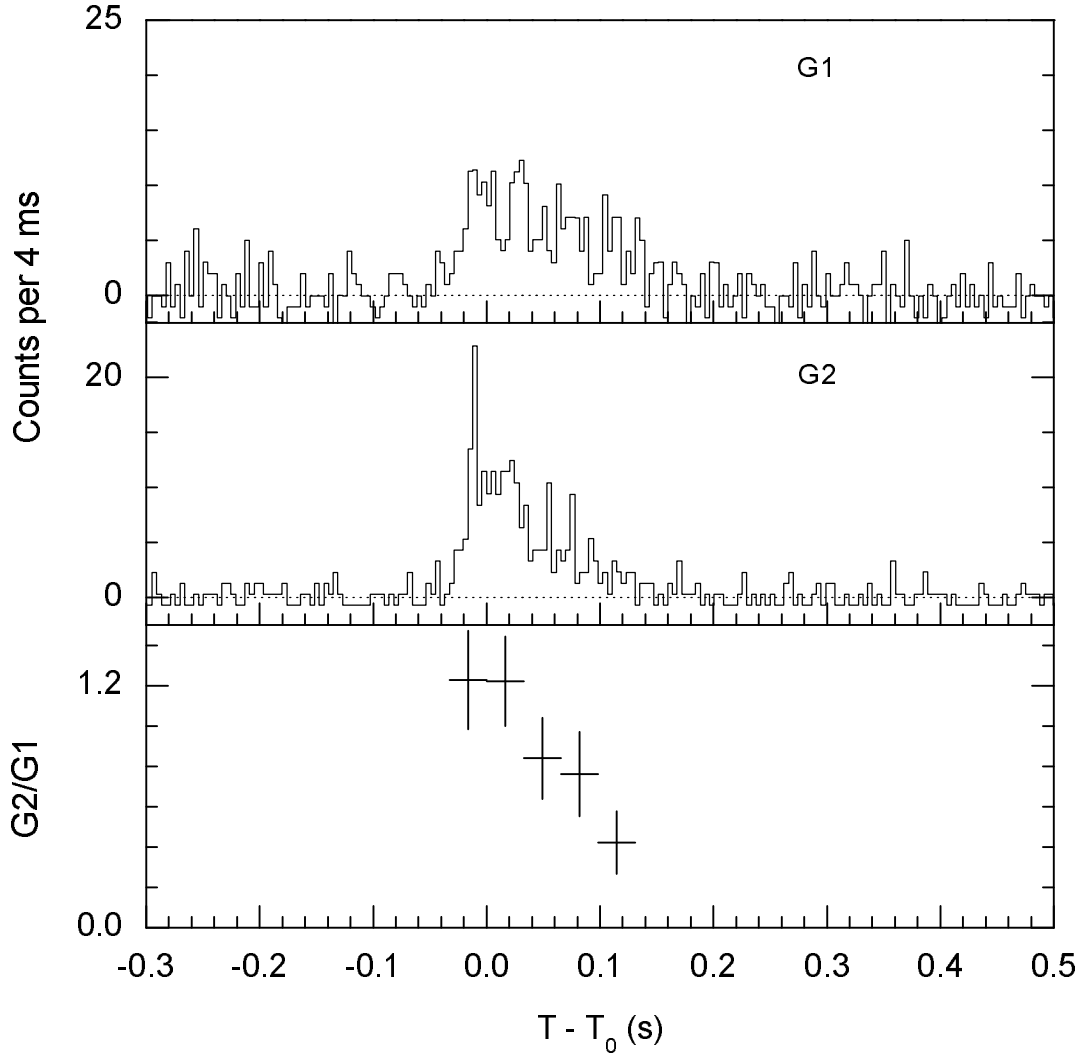


Fig. 3.— Time history of the initial pulse of the outburst reflected from the Moon as recorded by Helicon-Coronas-F spectrometer. Time profile of the reflected pulse $F(t)$ is seen during ~ 200 ms. Compared to the true profile of the initial pulse $I(t)$, it is spread, and the rise is less steep because of the signal being delayed in reflection from different regions on the spherical Moon. If t is measured in units of R_M/c , where R_M is the Moon's radius, and c is the velocity of light, $F(t) = \int_0^2 I(t - \tau)(1 - \tau/2)d\tau$.

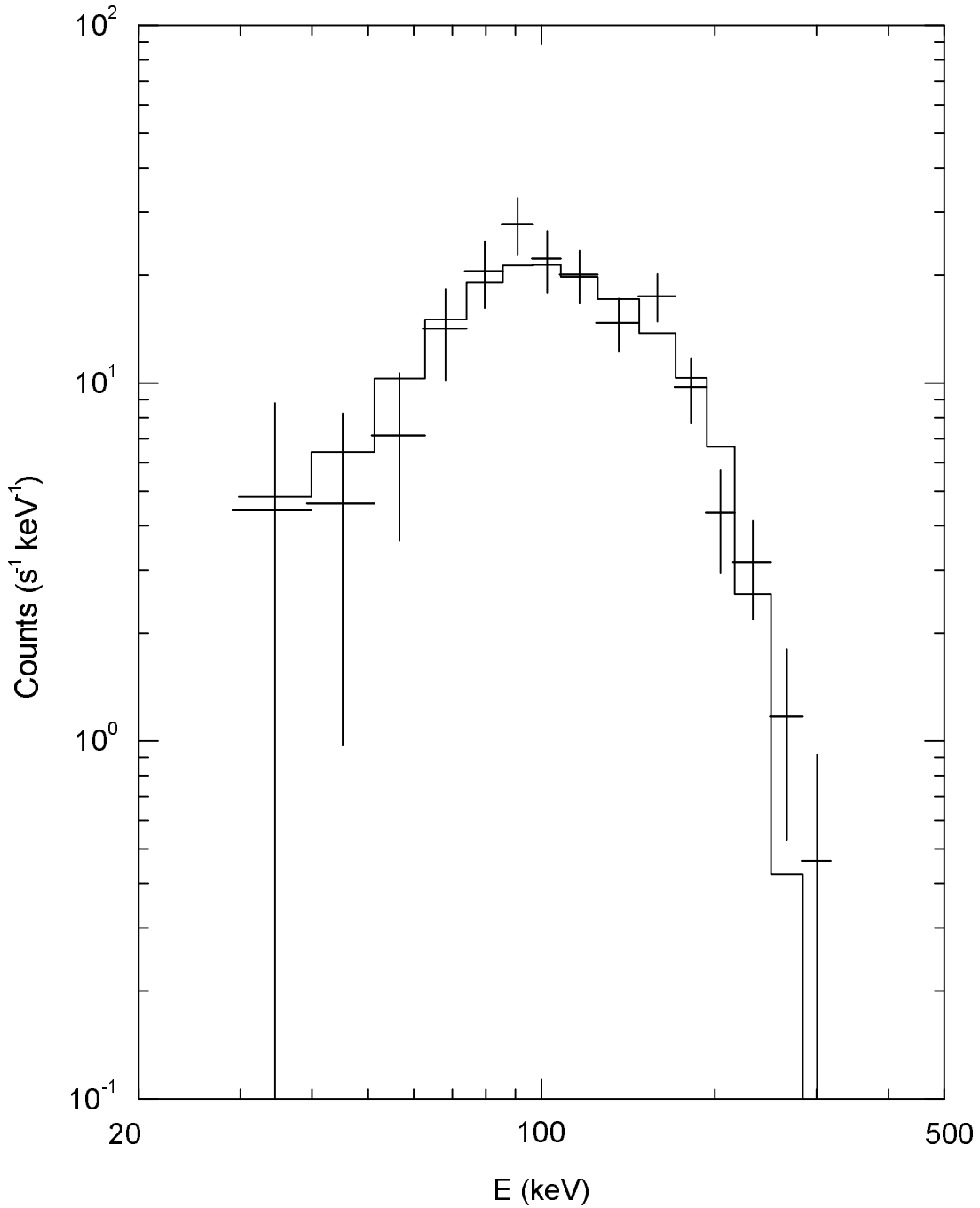


Fig. 4.— Energy spectrum of the reflected signal. The experimental points are shown with 1σ error bars. The histogram is the initial pulse spectrum in form of $dN/dE = A(E/100)^\alpha \exp(-E/E_0)$ modified by scattering from the lunar soil. The best-fit parameters are: $A = 1.55 \times 10^4$ photons $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$, $\alpha = -0.7$, $E_0 = 800$ keV ($\chi^2/d.o.f = 10.2/15$)

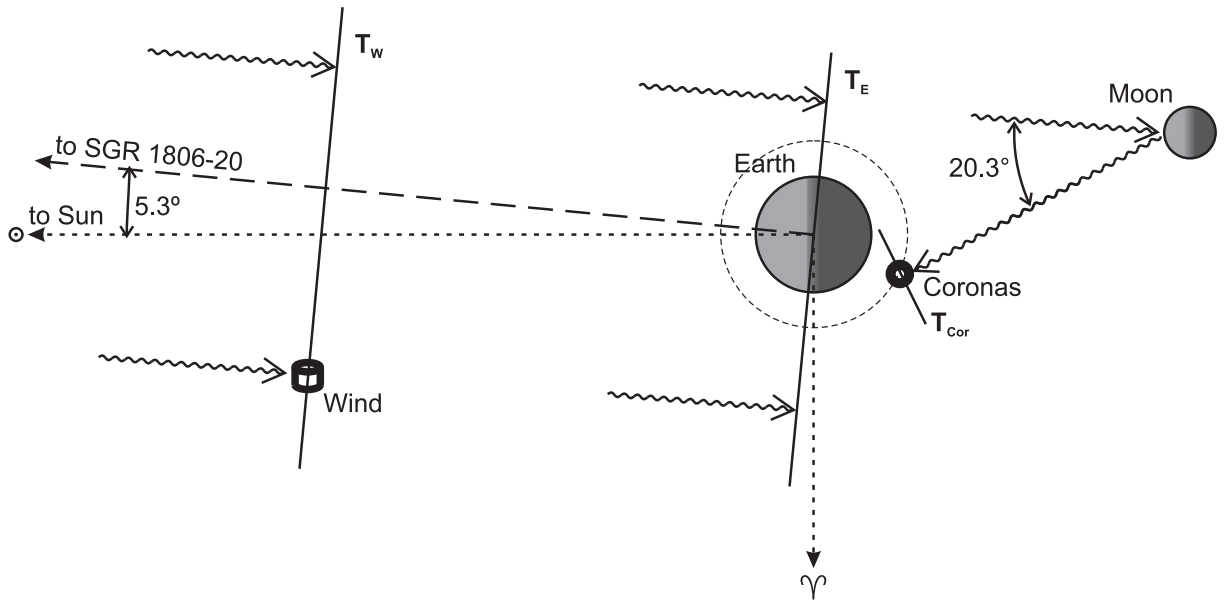


Fig. 5.— A schematic diagram of the flare detection by the Konus-Wind and Helicon-Coronas-F instruments. The flare wavefront came from the SGR 1806-20 direction, crossed Wind at T_W , passed Earth at $T_E = T_W + 5.086$ s, reached and was reflected by the Moon, and, finally, back-scattered radiation was detected by Helicon-Coronas-F at $T_{Cor} = T_W + 7.69$ s.

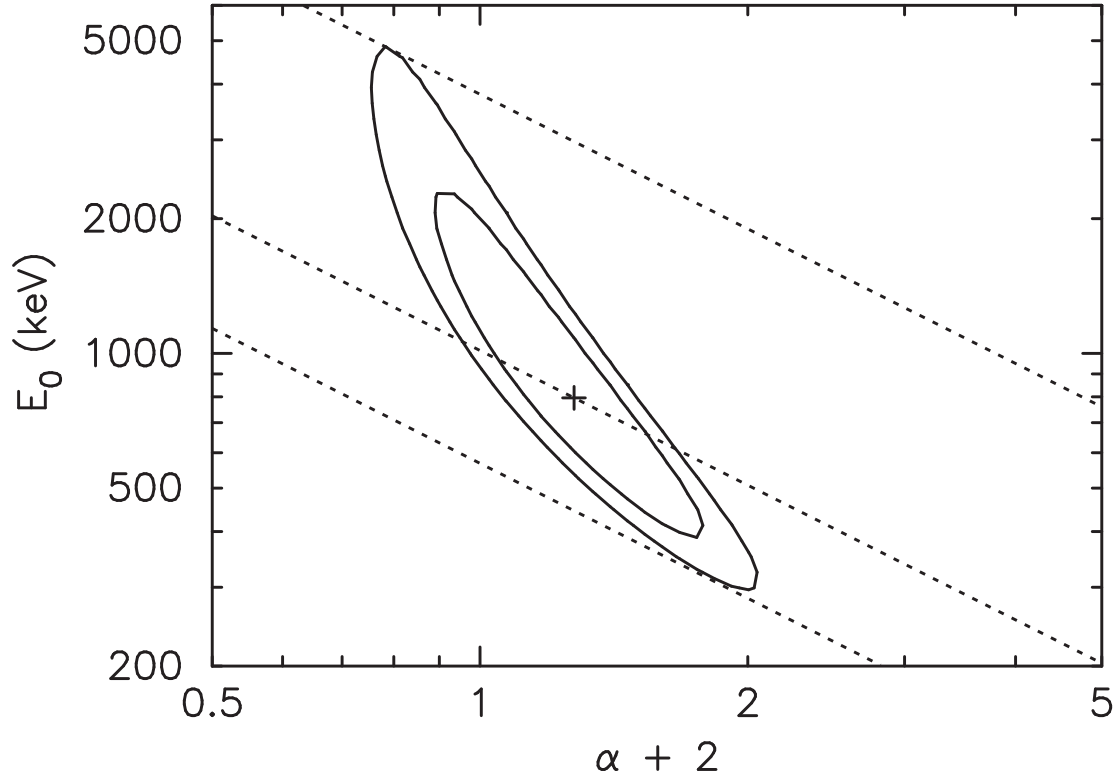


Fig. 6.— Contour plot for E_0 vs $(\alpha + 2)$ derived from the energy spectrum of the reflected signal. The two contours correspond to 68 and 90% confidence levels; the cross is relative to the best fit values of the two parameters. $E_{peak} = (\alpha + 2)E_0$ is the energy of the maximum in a νF_ν spectrum. Dependencies $E_{peak} = Const$ are also shown by dashed lines for $E_{peak}=0.6$, 1.0, and 3.7 MeV.

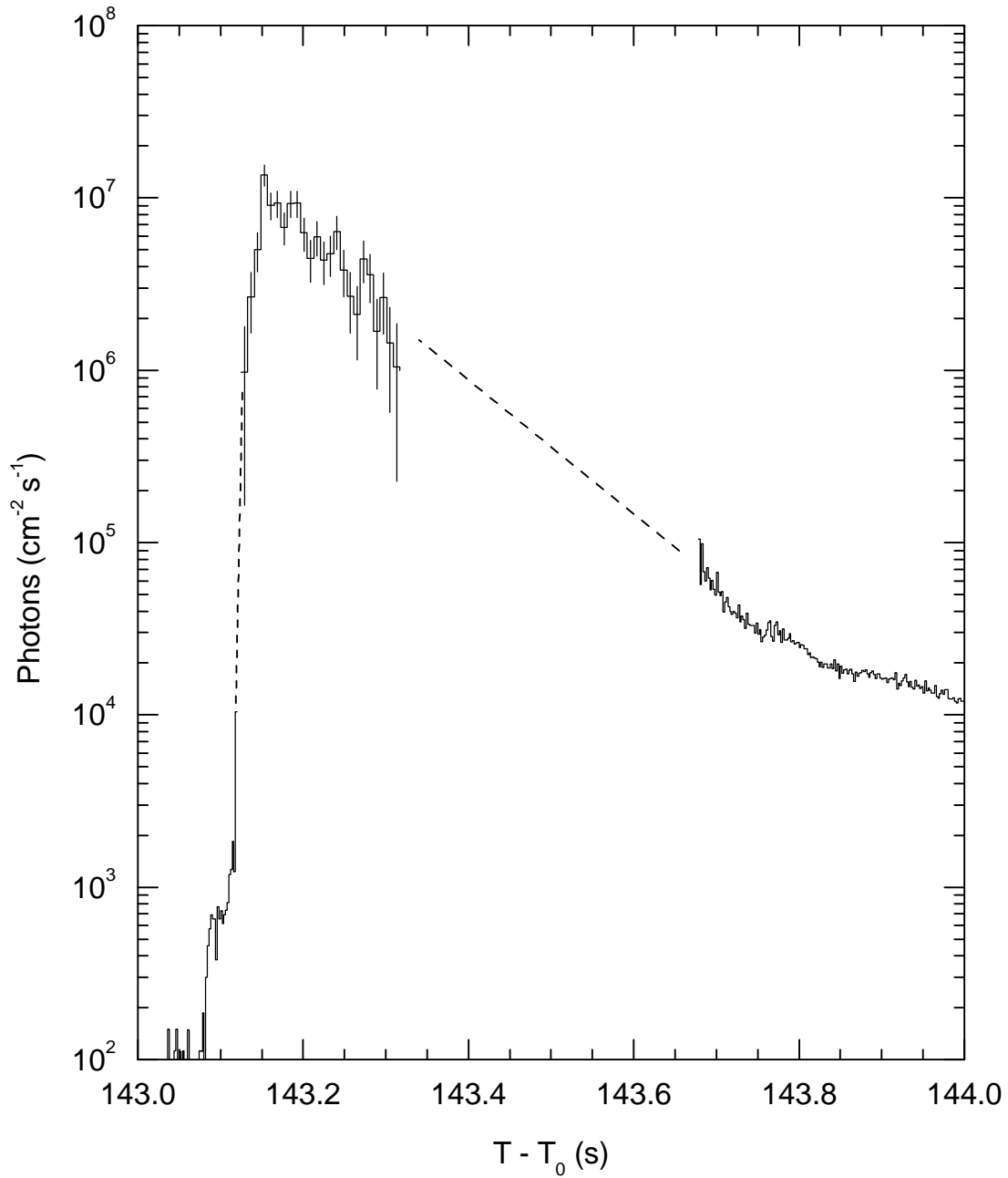


Fig. 7.— Reconstructed time history of the initial pulse. The upper part of the graph is derived from Helicon data while the lower part represents the Konus-Wind data. The dashed lines indicate intervals where the outburst intensity still saturates the Konus-Wind detector, but is not high enough to be seen by the Helicon.