High-Energy X-rays from the Crab Nebula

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by

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We have conducted a balloon measurement of the x-radiation from the Crab Nebula. Photons of high energy (~50 keV) from the Crab were first detected by Clark (1965); the present experiment has examined the energy range 23 keV to 455 keV with increased sensitivity and deduced a spectrum over a broader range than then possible. This letter discusses the x-ray spectrum at photon energies up to 90 keV.

The instrument employs a NaI (Tl) scintillator 10 cm in diameter and 5 cm thick. The energy resolution of the system is about 27%, full-width half-maximum, at 50 keV and about 16% at 150 keV. This scintillator and associated photomultiplier are surrounded by another NaI (Tl) crystal that is 30 cm long and 25.4 cm in outer diameter; it acts as a collimator. The wall thickness of the collimator is 7.5 cm on the sides and 10 cm in the back; six photomultipliers are associated with it. The two crystals are optically decoupled from each other, and the photomultipliers viewing the two are connected in anti-coincidence. A thin (0.64 gm/cm^2) plastic scintillator covers the 75 cm^2 aperture. The photomultipliers viewing the plastic are also

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connected in anti-coincidence with the tube viewing the central crystal. The anti-coincidence arrangement rejects pulses due to other radiation types such as cosmic rays. Additional angular collimation is provided by three 7.5 cm thick toroidal plastic scintillators spaced in front of the main assembly (see Fig. 1). Each of these three scintillators has an inner diameter of 10 cm and an outer diameter of 25.4 cm. The six photomultipliers viewing them are also connected in anti-coincidence with the central scintillator. The acceptance cone of the instrument varies slightly with energy; a typical value is 0.006 ster.

Pulses that are due to photons are analyzed by a balloon borne 128-channel pulse height analyzer, the gain of which is set to cover the desired energy range (23 to 455 keV). The output is digitally telemetered.

The instrument is pointed in flight at the Crab by a servo system that locks on the geomagnetic field in azimuth. An equatorial mount is provided. The polar axis is parallel to the earth's axis of rotation through compensation for the average geomagnetic declination along the trajectory. The instrument is clock-driven in right ascension about this axis at a rate of one revolution per day. Radio commands are provided to change the rate as the balloon changes longitude and also to provide an offset so that the background may be measured.

The balloon was launched from Palestine, Texas, at 2205 C.S.T., on October 19, 1965, and ascended to pressure altitudes varying between 4.35 mbar and 6.0 mbar, as measured by a photo-barograph carried aloft with the instrument. The flight was terminated by radio command at 0902 the following day. The Crab culminated at 0353 on 20 October (when corrected for balloon longitude), at 10 degrees south of zenith.

The instrument was recovered in good condition and the post-flight calibrations agree with those conducted prior to the flight. Thermostatically controlled heat was provided during the flight in order that the system gain should be constant, and the flight data exhibit no time dependence consistent with a gain change.

A battery failure occurred at 0610 C.S.T., thus limiting the time for measurement of the background at the floating altitude to 40 minutes, compared with 320 minutes of exposure to the Crab (plus background). The background was obtained in the interval 0010 to 0050, at an average zenith angle of 45°, just before the pointing system was turned on by radio command. The background is due to atmospheric radiation and to photons locally produced in the supporting structure, batteries, etc.

In the discussion that follows, the background has been normalized by a factor of 6.18 that is the ratio of the two average fluxes in channels 80-100 (295 keV-363 keV). The difference between this and the 8.00 ratio of the measurement periods presumably reflects the zenith-angle dependence of the atmospheric background (Frost et al., 1963), since (6.18/8.00) is equal to the ratio of the secants of the two average zenith angles.

Figure 2 shows the spectrum obtained while pointing at the Crab and the (normalized) background spectrum. The atmosphere and plastic scintillator strongly absorb x-rays at low energies; this results in the apparent peak at about 33 keV.

The difference between the two spectra has been corrected to the top of the atmosphere, taking into account the absorption factor, the path length through the atmosphere ($X \sec \theta$, where X is the depth and θ the zenith angle), the dead time of the system (~ 2%) and the geometric factor. Data at energies less than 33 keV have been rejected because of the very large corrections necessary for atmospheric absorption. The result is shown in Figure 3.

We have shown in Figure 3 for purposes of comparison the results of Clark (1965), who found an E^{-3} dependence of the photon flux on energy between 20 keV and 40 keV. There is rather good agreement in the region of overlap. The present experiment yields a flux below the upper limit set by the MIT experiment for energies in excess of 62 keV.

The recent determination by Peterson et al. (1966) is also shown in the figure. That experiment took place about 26 days prior to our measurement. The discrepancies between that determination and ours (as well as the Clark experiment) are not readily resolvable.

It is possible to approximate our spectrum with two power laws. Between 30 keV and 50 keV, one finds an $E^{-4.4}$ differential spectrum; an $E^{-9.2}$ variation may be fitted to the data between 50 keV and 74 keV, where these refer to the photon flux at the top of the atmosphere. But we should note that the results can be best approximated by a single exponential over the entire range. The expression is $(1.1 \pm 0.3) \exp \left[(-.119 \pm .005)E\right]$ photons $cm^{-2} sec^{-1} keV^{-1}$, where E is expressed in keV (see Figure 4).

The synchrotron mechanism produces a power law spectrum. However, as Burbidge et al. (1965) and Gould and Burbidge (1965) have recently remarked, the electron lifetime against synchrotron emission is only ~ 30 years << 911 years, the age of the Crab. A synchrotron source for high energy x-rays thus requires an active source of very high energy (~ 10^{14} ev) electrons assuming a 10^{-4} gauss magnetic field).

Bremsstrahlung from a hot gas, however, produces an exponential spectrum (Allen, 1963). The temperature deduced from the slope of the exponential curve fitted to the data by least squares in Figure 4 is $(9.5 \pm 0.5) \times 10^7$ °K.

One possible mechanism for generating this temperature is suggested by the observed high expansion velocity of the nebula (~ 1100 km/sec). A plasma streaming this fast will encounter shock waves wherever there are obstacles to the flow, such as the interstellar medium and the filaments in the Crab. A rather analogous situation exists at the earth's magnetosphere, where the solar wind velocity of ~ 400 km/sec results in temperatures of 10^7 °K immediately behind the collisionless shock that is in front of the magnetosphere (Bridge et al. 1965). The analogy suggests that a plasma speed of 1100 km/sec will produce temperatures $(11/4)^2$ as great, or about 10^8 °K at the shocks in and around the Crab. It should also be noted that Heiles (1964) and Burbidge et al. (1965) have suggested that a thermal bremsstrahlung model should be considered.

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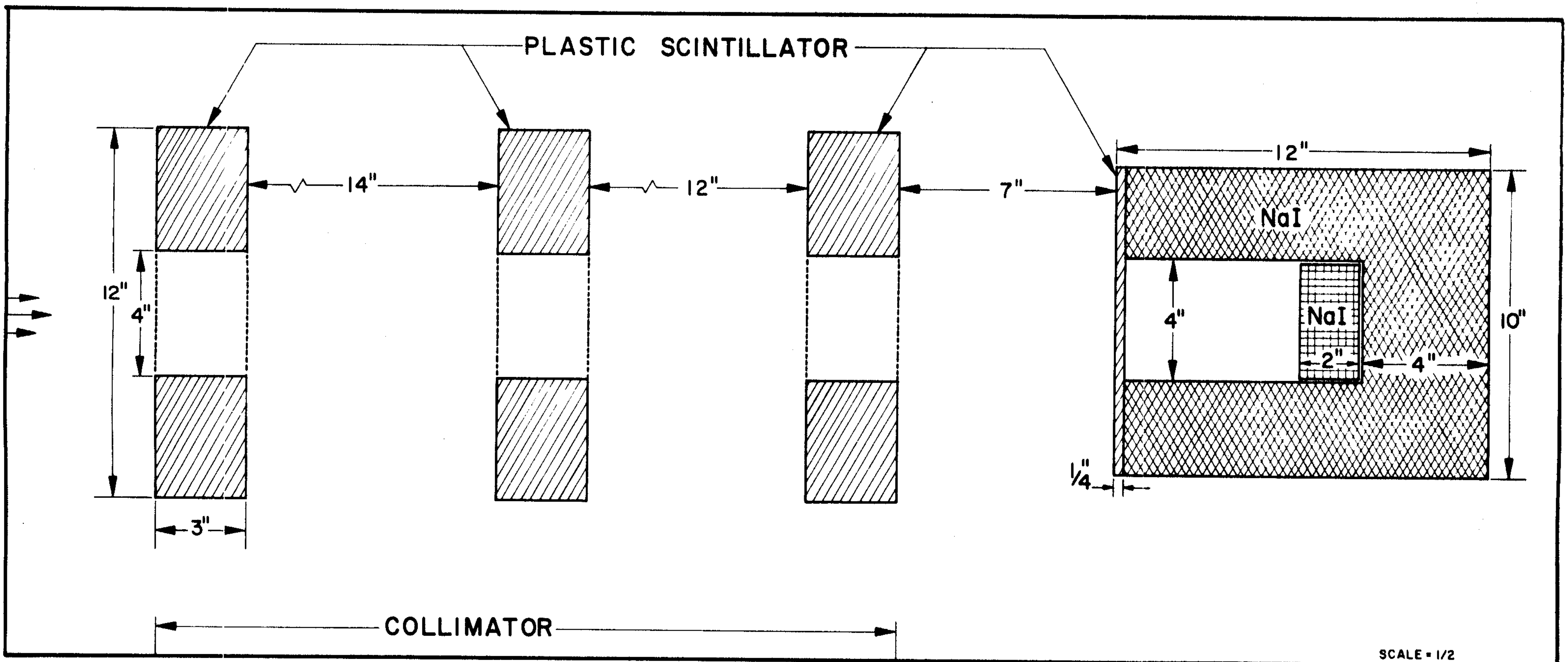
FIGURE CAPTIONS

Figure 1. Schematic view of the gamma-ray detector. The photomultipliers viewing the plastic scintillators as well as those viewing the cup-shaped NaI scintillator are connected in anti-coincidence with the photomultiplier associated with the central NaI scintillator.

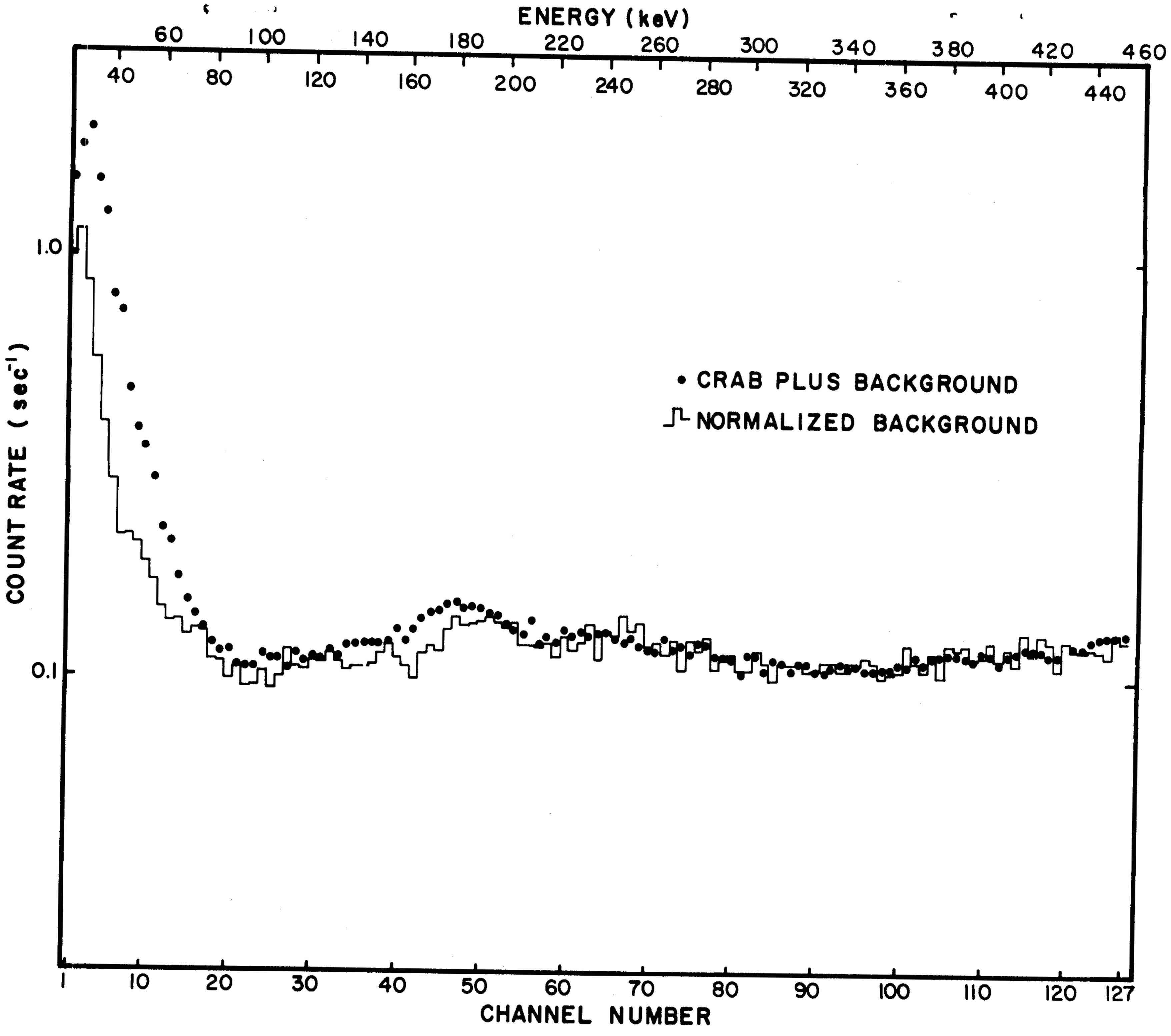
Figure 2. Pulse height spectra obtained while pointing at the Crab and while pointing away from the nebula. The exposure time was 320 minutes.

Figure 3. The x-ray spectrum from the Crab Nebula, corrected to the top of the earth's atmosphere. The present determination agrees well with that by Clark, in the region of overlap. It is also seen that a power-law spectrum is valid only over a narrow range of energies. The NRL data have been quoted by Clark and the Frost et al. results have been noted by Peterson et al.

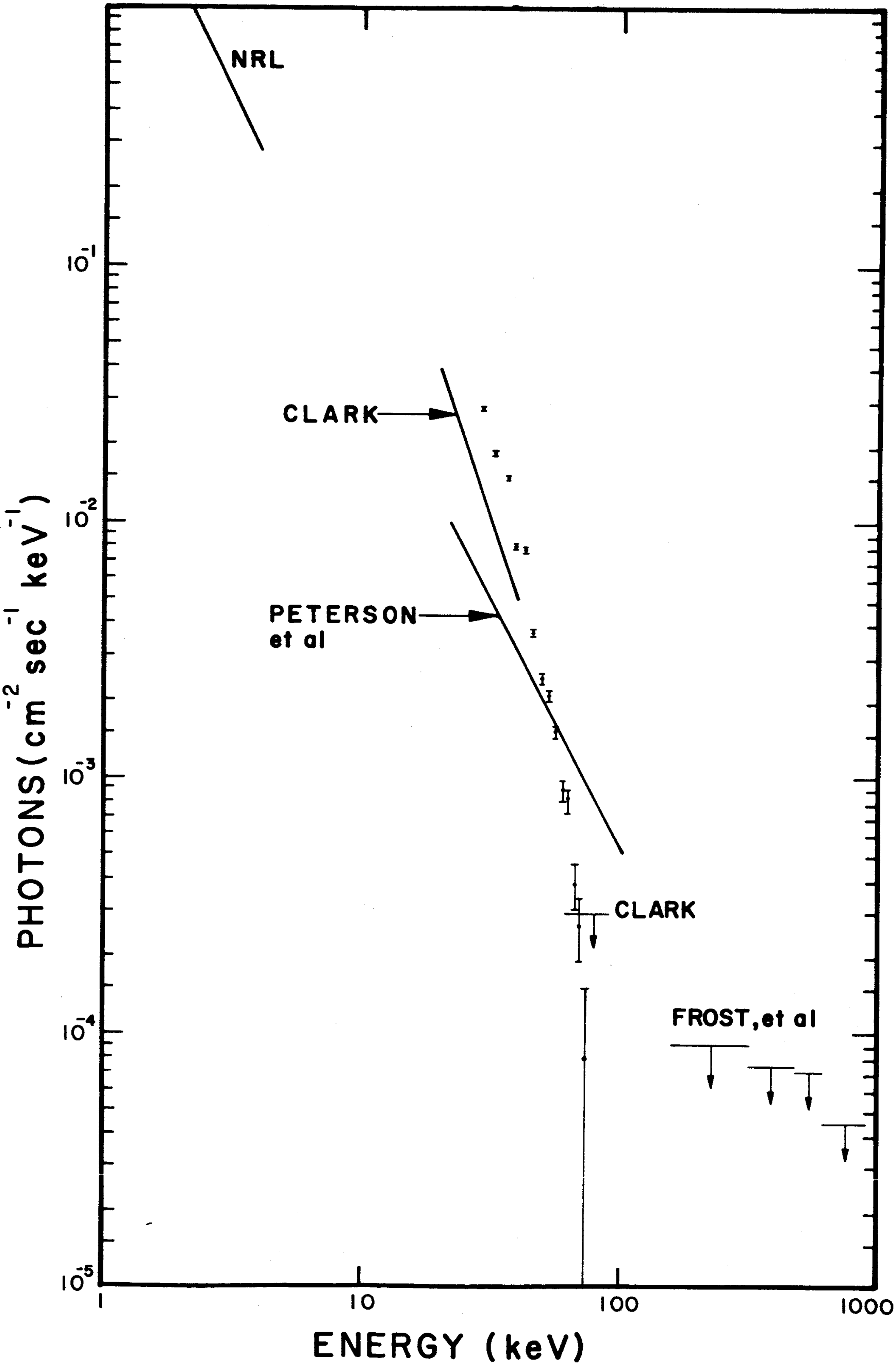
Figure 4. The data of Figure 3, replotted on semi-logarithmic coordinates. It is seen that a single exponential is a good approximation to the spectrum over the entire energy range. The slope of the exponential corresponds to a temperature of $(9.5 \pm 0.5) \times 10^7$ °K.



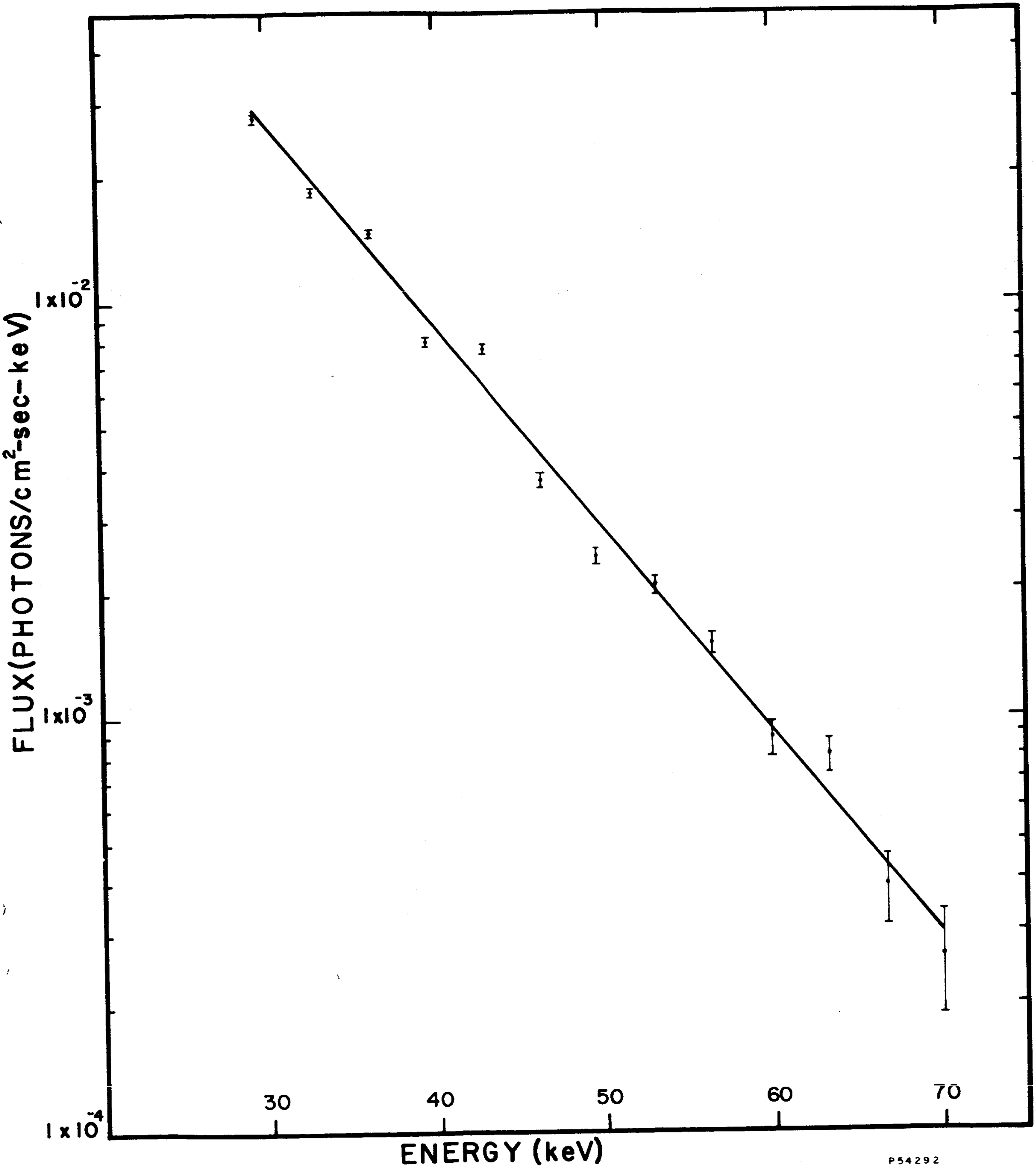
GAMMA RAY DETECTOR


ENERGY (keV)
60 100 140 180 220 260 300 340 380 420 460
40 80 120 160 200 240 280 320 360 400 440
COUNT RATE (sec^{-1})
1.0
0.1
• CRAB PLUS BACKGROUND
NORMALIZED BACKGROUND
1 10 20 30 40 50 60 70 80 90 100 110 120 127
CHANNEL NUMBER

P54290



NRL
CLARK
PETERSON et al
CLARK
FROST, et al
PHOTONS (cm^{-2} sec^{-1} keV^{-1})
ENERGY (keV)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1
10
100
1000



FLUX(PHOTONS/cm²-sec-keV)
1x10⁻²
1x10⁻³
1x10⁻⁴
30
40
50
60
70
ENERGY (keV)

P54292