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THE UPPER LIMIT SOLAR GAMMA-RAY SPECTRUM TO 10 MEV

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In this letter we wish to report new upper limits on solar γ-rays obtained from a balloon flight series in February 1966. These results, when combined with other recent work, form a composite upper limit γ-ray spectrum from the quiet sun over the range 20 kev to 10 Mev which is about a factor of 30 lower than that previously available. Since several experimental techniques were used to cover this large energy range, the results in the 20-200 kev range will be presented first, followed by the 1-10 Mev work. Upper limits in the 130-800 kev region are available from previous work (Frost, et al, 1966). In none of the observations reported here was there any indication of a statistically significant solar flux.

Observations in the lower energy range were obtained with the prototype version of an X-ray detector originally designed for an OSO satellite (Hicks, Reid, Peterson, 1965). This detector consists of a 3 mm thick x 10 cm^2 area NaI scintillation counter with an anticoincidence collimating shield of CsI. Since the inherent event rate of this detector is very low, the major contribution to the background comes from the atmospheric and cosmic X-rays entering the 0.15 steradian forward aperture. The detector was mounted in a balloon gondola with the elevation and azimuth servo-controlled, using optical solar sensors. Events from the 128-channel pulse-height analyzer, plus rate monitoring, servo housekeeping and temperature data were all transmitted on a PCM/FM/FM system. The apparatus, except for the modified servo control, is identical to that used in previous observations of cosmic X-ray sources (Peterson, Jacobson, Pelling, 1966) (Peterson and Jacobson, 1966). The general detector scheme, telemetry, servo system and data reduction procedures are also similar to that used by Frost, et al (1966) to obtain the results in the 130-800 kev range. For the observations reported here, the servo was programmed to track the sun for 40 minutes. The detector was then pointed at the same elevation in reverse azimuth direction for 20 minutes to obtain a background measurement. Five minutes of each background measurement were devoted to calibration with a Ba^{133} source. This sequence was repeated each hour.

The balloon carrying this instrument was launched at 0445 MST on February 18, 1966 from Phoenix, Arizona, reached ceiling altitude of 3.5 gm/cm^2 at 0725 MST and apparently floated level until flight termination at 1555. The sun reached its maximum elevation of 45^o at 1210 MST. A timer initiated the observing, background and calibration sequence at 0723.

Readouts of the azimuth and elevation independent of the servo loop verified the pointing and tracking operations. Pulse-height spectra obtained from a background measurement are subtracted from that obtained during the corresponding solar observation. These measurements, being at the same elevation angle, correctly account for dependence of the background on zenith angle. By correcting this difference for area, efficiency, dead time, and atmospheric absorption, statistically determined limits on the solar flux can be obtained. About 6.5 hours of total observing time were used to obtain the results reported here.

The counting rates and statistical significance of all the data used when observing the sun are indicated in Table 1, as well as the difference at 95% confidence level, corrected and extrapolated to zero depth. The channel groupings have been chosen, consistent with the energy resolution and spectral slope, to obtain the lowest possible limits. The results are also plotted in Figure 1 on a composite differential flux spectrum for the quiet sun. The higher energy data and the results of previous work are also indicated. Our upper limit spectrum over the 20 to 200 kev range is considerably lower than those obtained from the OSO-I satellite in March of 1962, and joins smoothly onto the results in the intermediate range reported by Frost, et al (1966) for June 10, 1962.

Since directional detectors which operate at higher energies present a considerable problem, the results in the 1-10 Mev range were obtained using a simple technique. A 3" x 3" NaI scintillation counter, which has an omnidirectional geometry factor of 67 cm^2 and nearly an isotopic response, was flown at 126,000 feet during a night-day flight. The solar flux is then obtained from the diurnal variation of counting rates. Considerable attention to instrumental detail is required to obtain a spectrum limited only by the counting statistics. The detector is surrounded with a 2.5 cm thick plastic scintillation shield, viewed by a second phototube and connected in electrical anticoincidence. This eliminates edge effects due to cosmic ray particles and reduces the counting rate in the 1-10 Mev range to about 47 c/sec. Each event is coded with a 128-channel pulse-height analyzer onto a digital system, in a manner identical to that described previously. Gain calibration is obtained by switching, through a known resistance network, to the 200 kev to 2 Mev range for about 5 minutes each hour. This brings the 0.5 Mev annihilation line, a prominent feature of the atmospheric γ-ray spectrum, into the range of the analyzer. The resolution of the detector at this energy is 14%.

The principal results at the higher energies to be reported here were also obtained February 18, 1966. Launch occurred the previous evening at 1859 MST and ceiling was reached at 2144 MST. This balloon also floated level at 3.6 gm/cm^2 until termination occurred at 0940 MST. Data obtained from 0300 to 0500 were subtracted from the spectrum between 0700 and 0900, when the sun was at least 35° above the horizon. Since no line structure was observed, the pulse height channels here have also been combined to form appropriate energy groupings. Table I indicates the rate over these intervals, the statistical error, and the upper limit γ-ray flux at a 95% confidence level. This flux is obtained once again by correcting the counting rate difference for area, channel width and atmospheric depth. No corrections for efficiency have been applied here, allowing a direct comparison with previously reported results in the 1-10 Mev range. These results are also shown in Figure 1, as well as results obtained in an earlier observation with the same apparatus on June 27, 1965. The considerable reduction in upper limits on the most recent flight occurred by reducing systematic uncertainties and improving data acquisition procedures.

All these data form a complete set of upper limits on the quiet sun γ-ray flux over the 20 kev to 10 Mev range. The usual indicators of solar activity, flares, sunspot number, radio emmission, etc. showed none of the variations or enhancements which characterize an active sun. (Preliminary report of Solar Activity, February 25, 1966), (Compilations of Solar-Geophysical Data, March 1966, June 1966). These new limits are statistically determined at about 3% of the atmospheric γ-ray flux at 3.3 gm/cm^2 and $\lambda = 40^o$ magnetic. As indicated in the figure these limits are about one and a half orders of magnitude lower than those previously available. Atmospneric absorption limits balloon observations to energies above about 20 kev.

Also shown in the figure are rocket data obtained at lower energies by the Livermore group in June 1965 (Chodil, 1965) fitted to an optically thin hot gas at 4.5×10^{6} °K. Extensive measurements of these X-rays, the "2 - 8 Å region", due to the solar corona or hot regions above active centers have been made by Friedman and his associates (Kreplin, 1962). Since the observations indicate that these fluxes are highly variable in time, the concept of a "quiet sun" may not be applicable to this spectral region. During solar flares, fluxes many times above these limits have been occasionally observed, having energies up to several hundred kev (AAS-NASA Symposium, 1964)

Dolan and Fazio (1965) have recently reviewed the observations and theory regarding the solar γ-ray spectrum. Based on present understanding of solar processes, the most probable γ-ray emission process is due to cosmic rays interacting near the solar surface and producing secondary γ-ray albedo. Thermonuclear reactions in the solar atmosphere, once suggested as an important source, have been shown to contribute neglectable fluxes, most likely even during solar flares. However, γ-ray emission will occur on the quiet sun due to the naturally occurring radioactive isotopes. These γ-ray lines can be predicted, based on the abundances quoted by Goldberg, Muller, and Aller (1960) for the chromosphere. One assumes sufficient mixing takes place so that the upper 30 gm/cm^2 of the photosphere has the same element ratios as the chromosphere. The predicted fluxes, considerably below the present upper limits, are 0.48×10^{-8} photons/cm^2-sec at 1.48 Mev due to K^{40}, and 0.21×10^{-8} photons/cm^2-sec due to Th^{228}.

Cosmic-ray produced γ-rays can be estimated from measurements on terrestrial albedo. This intensity, shown in the Figure, is obtained by dividing the background at 3.6 gm/cm^2 by a factor of 1.5 which extrapolates to zero depth, multiplying by 3 to correct from $\lambda = 40°$ to $\lambda = 0$, and accounting for the solid angle ratio $\frac{.25 \times 10^{-3}}{8\pi}$. As indicated by the dashed line, this albedo must join the extension of the coronal spectrum in the 8 - 20 kev range. This assumes the full intensity of galactic cosmic rays is indeed incident on the solar surface. Most likely this condition is not obtained due to solar and interplanetary magnetic fields; therefore the estimated albedo is an upper bound. For example, if the surface dipole field is 1 gauss, the resultant magnetic cutoff for protons traveling in the meridian plane and arriving at the equator would be 1000 bev, and only 10^{-3} part of the cosmic ray intensity would reach the solar equator. Random fields in the interplanetary medium could produce a similar effect.

Although these new upper limits put considerable constraints on non-thermal process, and are at a level much below previous measurements, further reduction is needed. In particular, it would be desirable to place upper limits at the level of the "estimated albedo". This requires only about a factor of 30 increase in sensitivity over the 20 - 100 kev range. The techniques to accomplish this are under development now, however at the higher energies nearly a factor of 10^3 is needed. Here the methods of achieving such low backgrounds and high collimations are not yet even in a conceptual stage.

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Figure 1

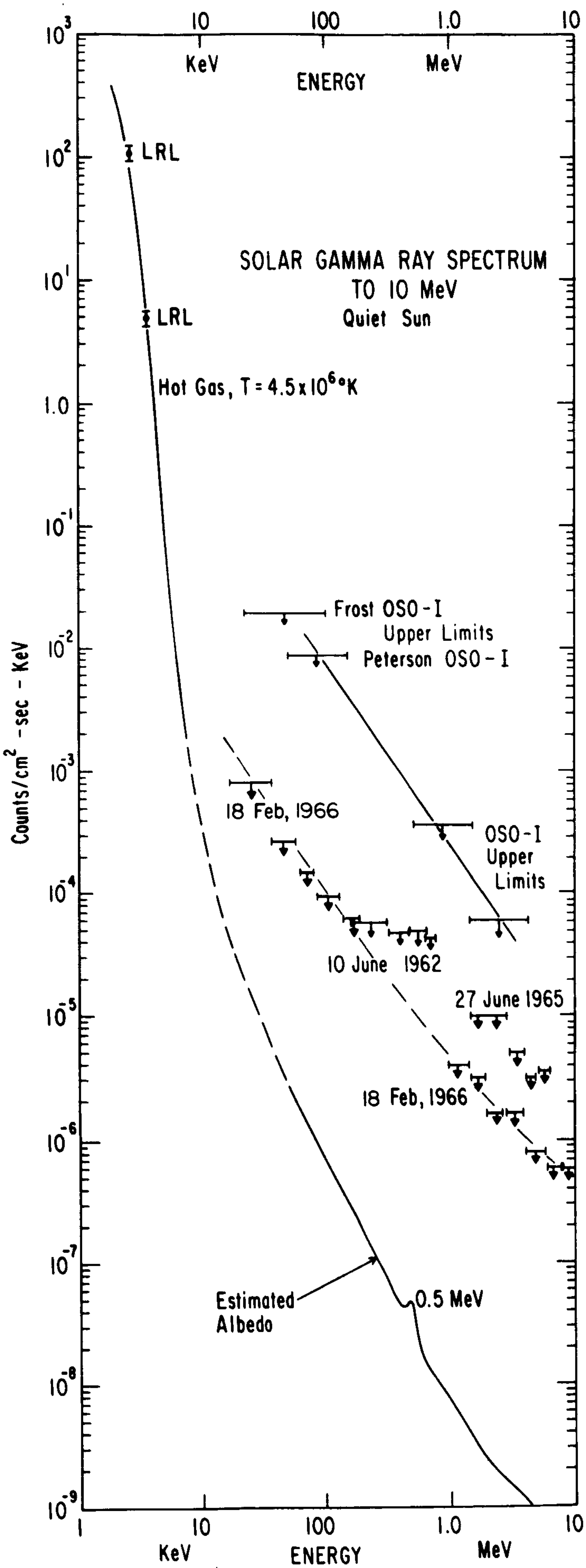
Measurements and estimates on the quiet sun γ-ray spectrum. The present upper limits from a series of balloon observations on February 18, 1966 are about a factor of thirty below the previous observations from the OSO-I. The hot solar corona produces a steep free-free emission spectrum which must join smoothly onto the estimated albedo flux due to cosmic-ray interactions in the solar surface.

TABLE I

BACKGROUND FLUXES AND SOLAR UPPER LIMITS

February 18, 1966

Energy Range kev	Typical Counting Rates counts/sec	Maximum Difference 2σ level counts/sec	Solar Flux Upper Limit counts/cm^2-kev-sec
17.5 - 37.5	.278 ± .005	1.94×10^{-2}	8.1×10^{-4}
37.5 - 60.0	.252 ± .005	2.10×10^{-2}	2.7×10^{-4}
60.0 - 80.0	.173 ± .003	1.20×10^{-2}	1.5×10^{-4}
80.0 -135.0	.414 ± .005	2.10×10^{-2}	$.9 \times 10^{-4}$
135.0 -185.0	.255 ± .003	1.00×10^{-2}	$.6 \times 10^{-4}$
Mev			
1.0 - 1.5	10.7 ± .05	.13	4.0×10^{-6}
1.5 - 2.0	6.30 ± .04	.11	3.2×10^{-6}
2.0 - 3.0	8.24 ± .04	.11	1.6×10^{-6}
3.0 - 4.0	5.63 ± .03	.11	1.6×10^{-6}
4.0 - 6.0	7.26 ± .04	.11	0.8×10^{-6}
6.0 - 8.0	4.11 ± .03	.080	0.6×10^{-6}
8.0 - 11.0	4.06 ± .03	.12	0.6×10^{-6}



SOLAR GAMMA RAY SPECTRUM
TO 10 MeV
Quiet Sun
ENERGY
KeV
MeV
Counts/cm² -sec - KeV
LRL
LRL
Hot Gas, T = 4.5 x 10⁶ °K
Frost OSO-I
Upper Limits
Peterson OSO-I
18 Feb, 1966
OSO-I
Upper
Limits
10 June 1962
27 June 1965
18 Feb, 1966
Estimated
Albedo
0.5 MeV

FIGURE 1