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GAMMA-RAY SPECTROSCOPY OF THE GALACTIC CENTER REGION: CONFIRMATION OF THE TIME-VARIABILITY OF THE POSITRON ANNIHILATION LINE

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Abstract

The GSFC Low-Energy Gamma-Ray Spectrometer observed the region of the galactic center during a balloon flight from Alice Springs, Australia, on 1981 November 20. No significant excess over background was evident in the 511 keV annihilation line. We derive a 98 percent confidence upper limit for this line of 1.2×10^{-3} photons/cm^2-s. Continuum emission was detected above 100 keV with a best-fitting power law spectrum of the form $dN/dE = A(E/100)^{-\alpha}$ where $A = (1.9 \pm 0.4) \times 10^{-4}$ photons/cm^2-s-keV and $\alpha = 2.35^{+0.5}_{-0.4}$. These results confirm the recent observations of time-variability by HEAO-3 (Riegler et al. 1981, 1982). A compact source at or near the galactic center provides the most satisfactory agreement with all of the data.

I. Introduction

The first observation of a spectral feature which could be confidently identified as a gamma-ray emission line from a cosmic source was reported by Leventhal, MacCallum, and Stang (1978). The line, originating in the region of the galactic center, was at an energy of 511 keV, corresponding to the positron-electron annihilation radiation. Earlier measurements by Johnson and Haymes (1973) and Haymes *et al.* (1975) had shown spectral features in the same energy range, but the systematic uncertainties in these experiments were too large to permit positive identification of the features. These observations aroused considerable interest because the annihilation radiation might provide unique information about high energy processes in the central region of our galaxy and perhaps lead to further advances in our understanding of galactic nuclei in general.

Subsequent observations by Leventhal *et al.* (1980) and Albernhe *et al.* (1981) confirmed the existence of the line, but some of its most important characteristics were discovered with the JPL gamma-ray spectrometer on the HEAO-3 satellite (Riegler *et al.* 1981). These data provided not only the strongest constraints on the energy (510.9 ± 0.25 keV) and width (< 2.5 keV FWHM) of the line but also showed significant evidence for variability in intensity on a 6-month timescale. Although HEAO-3 also measured the location and spatial extent of the source, the magnitude of the flux variability alone would argue in favor of the origin of the line in a single point source, a fact which immediately rules out many theoretical models of the origin of the line.

Several authors (Stecker 1969; Leventhal 1973; Bussard, Ramaty, and Drachman 1979) have stressed the possible astrophysical significance of positronium formation during the positron annihilation process. Annihilation from positronium results in both a line feature at 511 keV (from the singlet state) and a broad continuum below 511 keV (from the triplet state). The relative contributions of line and continuum photons depend on properties of the annihilation region such as density, temperature, and ionization fraction. Leventhal, MacCallum, and Stang (1978) presented evidence for a positronium continuum, but a subsequent flight (Leventhal et al. 1980) was not sufficiently sensitive to confirm this.

The continuum gamma-ray flux from the galactic center is also of interest because models of the line emission may imply a relation between the low energy gamma-ray continuum luminosity and the line flux. This possibility was discussed by Riegler et al. (1982) who presented evidence from the HEAO-3 data for a correlation between the line and continuum variations.

II. Instrumentation

The Goddard Low-Energy Gamma-Ray Spectrometer (LEGS) employs a cluster of three cooled-germanium detectors with a total active volume of 250 cm^3 which results in effective area of 11.8 cm^2 at 511 keV and a peak effective area of 32.7 cm^2 at ~ 130 keV. The average instrumental energy resolution rises gradually from 1.8 keV (FWHM) at 70 keV to 3.5 keV at 2.6 MeV with a typical value of 2.2 keV at 511 keV. An active NaI shield collimates the field-of-view of the detectors to ~ 15^o FWHM.

The instrument is enclosed in an aluminum pressure vessel and mounted in a servo-controlled gondola which uses an alt-azimuth pointing system referenced to the Earth's magnetic field and the local vertical. Observations are normally performed by tracking a target in the sky to a precision of ± 0.5^o under the control of an onboard microprocessor. Background is determined by offsetting the system by 180^0 in azimuth from the target direction while keeping the elevation angle the same as that of the target. These modes are alternated every 20 minutes over the observing period.

In-flight energy calibration is determined by monitoring the strong background lines at 54, 67, 140, and 198 keV (produced by neutron activation of the Ge detectors) and the 511 keV annihilation line.

III. Observations

The LEGS instrument was launched on a 2.6×10^7 ft^3 balloon from Alice Springs, Australia, on the morning of 1981 November 20 (local time). The package reached a float pressure of 3.4 mb at 22:15 UT (November 19) and was cut down at 09:04 UT (November 20). The first target was the giant radio galaxy Cen A, and the data thus obtained are currently being analyzed. The galactic center was the second target, and preliminary results have been presented previously (Paciesas *et al.* 1982; hereafter paper I).

Observations of the galactic center were initiated at 01:05 UT. Soon after this, however, a malfunction of the pointing system forced us to switch to a drift-scan mode for the meridian transit portion of the galactic center observation (03:20-07:10 UT). Following this we were able to resume normal operation for a period of 1 hour (07:20-08:20 UT) at which time a recurrence of the malfunction forced us to terminate our observing program.

For analysis, the data in the energy range from 70 keV to 2 MeV were divided into 12 continuum energy bins, excluding the strong background lines at 140 and 198 keV, plus one bin of 4 keV width centered on 511 keV. The latter bin was subjected to the same analysis as the continuum data in order to detect the presence of any source flux (line or continuum) in the region of the 511 keV line. A visual inspection of the 511 keV line flux versus time during the drift scan (Figure 1 of Paper I) gave no indication of a significant galactic center flux. We note here that, contrary to the description in the text of Paper I, the plot shows the raw rate per detector. The total live time corrected LEGS background rate in the 511 keV line is ~ 0.04 counts/s.

The pointing data, consisting of two 20-minute on-source intervals and one 20-minute background interval, were analyzed by simple subtraction of the off-source rate in each bin from the weighted mean of the on-source rates, with correction for instrumental dead time included. Drift scan data were analyzed by dividing the scan into intervals of ~ 20-minute duration and calculating the average fractional exposure of each detector to the galactic center over each interval, taking into account the energy dependence and the azimuthal dependence of the collimator transmission. The count rates R_{ijk} for each time interval i, energy bin j, and detector k were corrected for instrumental dead time and fit using standard least-squares techniques to a function of the form $R_{ijk} = B_{jk} + f_{ijk} S_{jk}$, where f_{ij} is the fractional exposure to the galactic center, S_{jk} is a constant source rate and B_{jk} is a constant background rate.

This technique produced fits which were statistically acceptable and source fluxes which were consistent with the pointing results, with two exceptions. Firstly, in the energy range below ~ 100 keV the assumption of a single point source located at the galactic center which was used to calculate the fractional exposure is probably invalid and a more complicated deconvolution is required (cf. Dennis et al. 1980). Therefore, data below 100 keV have been excluded from further treatment herein.

Secondly, the energy range between 520 and 1000 keV was found to exhibit a secular increase in the background rate with time during the flight, the variation being present in all three detectors at approximately the same rate. Variations in altitude or cosmic ray cutoff can in principle produce such an effect, but a comparison with previous analyses (e.g., Gruber 1974) suggests that these are inadequate to account for either the magnitude or time history of our variation. The altitude during the drift scan varied by less than 0.3 mb and the magnetic latitude by less than 0.7°, neither change being monotonic. More likely, the effect represents the activation by particle radiation of a relatively long-lived isotope but a detailed explanation is unnecessary for the analysis of the data.

We found by inspecting all of the float data that, in the energy range where the background variation was observable, it was approximately linear with time. Therefore, the data bins above 300 keV were fit using a function of the form $R_{ijk} = B_{jk} + T_i \dot{B}_{jk} + f_{ijk} S_{jk}$, where T_i is the time and $\dot{B}_{jk}$ the rate of change of the background. A statistically significant value of $\dot{B}_{jk}$ was obtained only in the 520-1000 keV bin. The resulting rate of increase was $\sim$ 2 percent per hour, compared to a signal-to-background ratio in this bin of $\lesssim$ 6 percent.

The observed source count rates were derived by summing the results from the individual detectors and taking the weighted average of the rates thus obtained for the pointing mode and the drift scan mode. The bin containing the 511 keV line showed no excess flux, the 1σ error being 5.2×10^{-3} counts/s. Doubling this number and correcting for detector effective area, absorption by intervening material in the instrument, and the residual atmosphere, yields a 98 percent confidence upper limit of 1.2×10^{-3} photons/cm^2-s.

The continuum data were fit by constructing model power-law spectra of the form $dN/dE = A\ (E/100\ \mathrm{keV})^{-\alpha}$ and convolving these with a response matrix including absorption by intervening material, detector full-energy peak efficiency, and the effects of partial energy loss via Compton scattering in the detector. The latter had been excluded from the analysis in Paper I. Escape peaks were not significant in this computation and were therefore not included. The intensity A and spectral index α were varied to minimize χ^2. The best fitting values $A = (1.9 \pm 0.4) \times 10^{-4}$ photons/cm^2-s-keV and $\alpha = 2.35^{+.5}_{-.4}$ produced $\chi^2 = 2.4$ for 7 degrees of freedom. The errors quoted represent independent 68 percent confidence ($\chi^2_{min} + 1$). The detector count rates were converted to the top of the atmosphere using channel-by-channel efficiencies calculated from this best-fitting spectrum. The results are displayed in Figure 1 where we also show the joint 95 percent confidence error limits ($\chi^2_{min} + 6$) on the model parameters.

IV. Discussion

Our results show no evidence for 511 keV line emission from the galactic center and thus strengthen the case for variability indicated by the HEAO-3 measurements (Riegler *et al.* 1981). Leventhal *et al.* (1982) arrived at similar conclusions from balloon flight data obtained 1 day after our flight. In fact, all of the results since the beginning of 1980 are consistent with the line emission being in a persistent "low" or "off" state.

The strongest limitation on the size of the line emitting region is still provided by the HEAO-3 observation of variability on a 6-month timescale. By the usual light travel time arguments, this implies a maximum size of the order of a light year. Ramaty and Lingenfelter (1981; also see Lingenfelter and Ramaty 1982) summarized the constraints placed on theoretical models by gamma-ray, infrared, and radio observations and concluded that an accretion disk around a massive compact object gave the most satisfactory agreement with the data. In such a model, the observed (e.g., Lacy _et al_. 1980) warm clouds of ionized gas within Sgr A (west) would be ionized by ultraviolet emission from the accretion disk. Nonthermal low-energy gamma-ray emission and e^+-e^- pairs would also be produced in the disk, the positrons subsequently annihilating in the ionized clouds to produce the 511 keV line.

If a mechanism such as that proposed by Lovelace, MacAuslan, and Burns (1979) and Blandford (1979) is responsible for the pair production in such a disk, one would expect a correlation between the low energy gamma-ray continuum and the 511 keV line intensity. In order to investigate this we have calculated the integral flux between 110 and 300 keV from four previous observations which are systematically similar to ours and for which the relevant data were available. The results are plotted in Figure 2 as a function of 511 keV line intensity. Our limit is represented by its 1σ value in accordance with the quoted errors in the other values.

Such a comparison is necessarily vague because the observed continuum may be produced, at least in part, by unrelated sources. In particular, the larger field-of-view (35^o) of the HEAO-3 instrument may produce a systematic difference between the HEAO-3 points (open circles) and the other data in Figure 2. HEAO-1 measurements (Matteson 1982) suggest, however, that the emission above 100 keV is dominated by a source (or sources) close to the galactic center, so that the field-of-view difference is probably not important. Thus, the slight indication of a trend in Figure 2 may be a real source effect. Further observations, preferably with better angular resolution, will be necessary to confirm this. The data in Figure 2 are certainly not inconsistent with the correlation hypothesis.

In any case, we note that both our continuum intensity and our line intensity are inconsistent, at least at the 95 percent confidence level, with the respective fall 1979 HEAO-3 data but are in general agreement with the spring 1980 HEAO-3 data.

In summary, we have observed continuum low-energy gamma-rays from the galactic center which are well fit by a power-law spectrum between 100 keV and 2 MeV. At the same time, we find no evidence for a narrow 511 keV emission line. In the context of previous results, our observations confirm the variable nature of this feature and are in general agreement with, but do not require, a model in which the continuum and the line are correlated.

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Figure Captions

Figure 1. Continuum spectrum above 100 keV from the galactic center region. The inset shows the 95 percent confidence (χ^2_{min} + 6) region of allowed values of the intensity A (at 100 keV) and spectral index α of a power-law spectrum. The best-fitting spectrum is also shown superimposed on the data points.

Figure 2. Flux in the 511 keV line plotted as a function of the 110-300 keV continuum flux. Only those measurements with systematic errors similar to ours are shown. Open circles are from Riegler *et al.* (1981, 1982). The filled circle is from Leventhal, MacCallum, and Stang (1978). Both values quoted by Leventhal *et al.* (1980) are shown as open squares; the authors' preferred value is drawn with solid lines. Our limit (filled triangle) is represented by its 1σ value, in accordance with the errors in the other points.

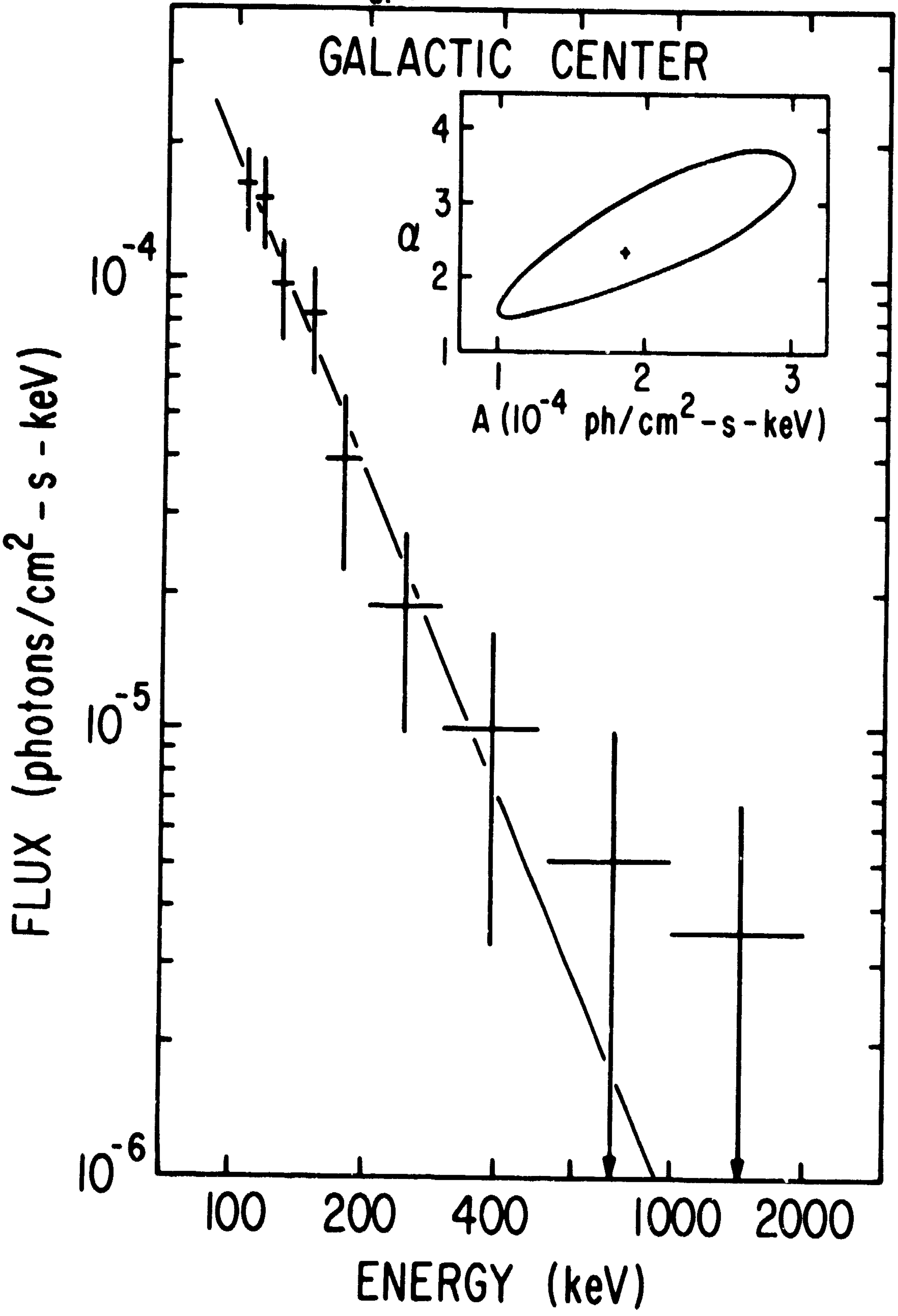
GALACTIC CENTER
FLUX (photons/cm^2 - s - keV)
10^{-4}
10^{-5}
10^{-6}
100
200
400
1000
2000
ENERGY (keV)
α
4
3
2
1
1
2
3
A (10^{-4} ph/cm^2-s-keV)

FIGURE 1

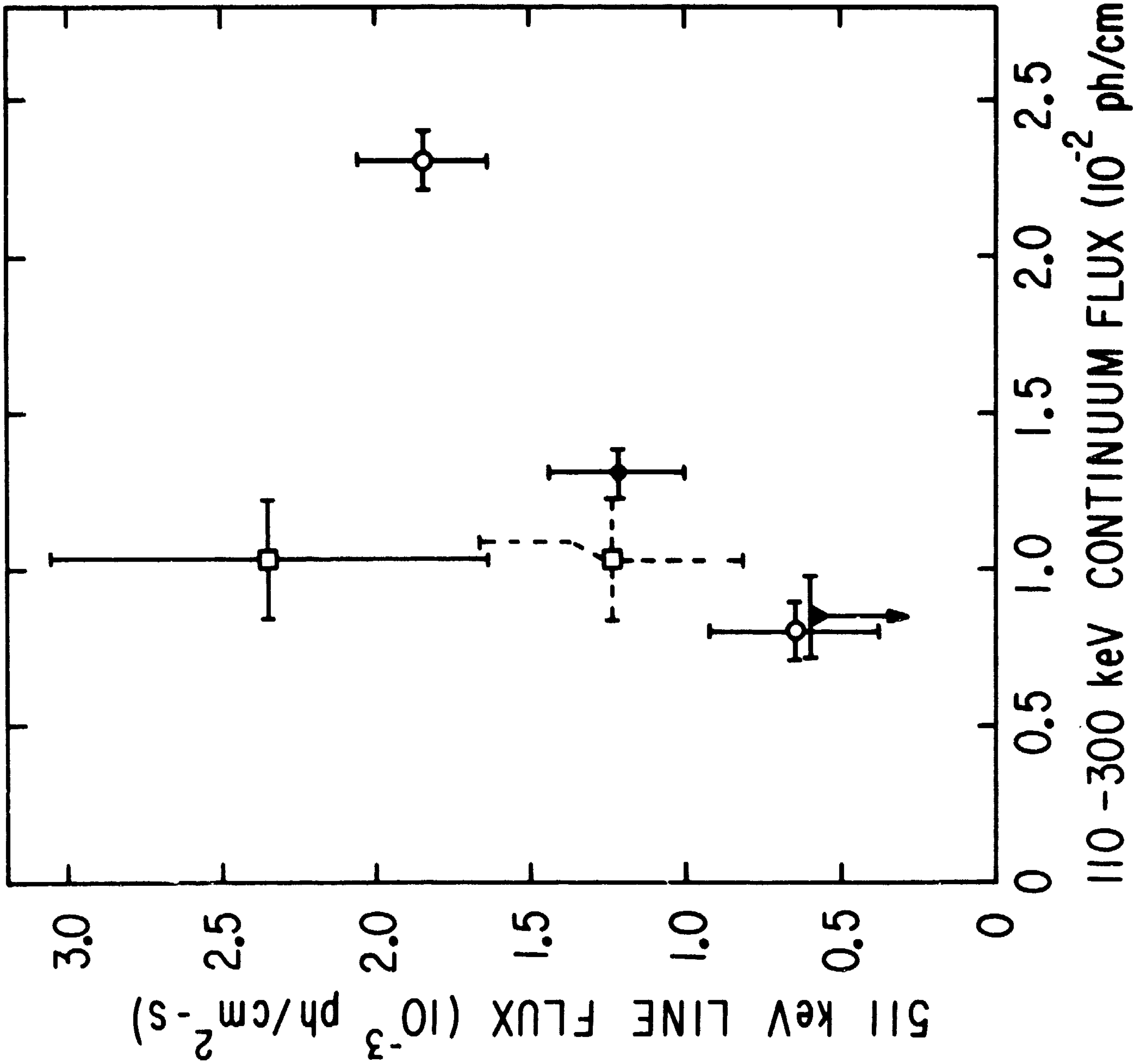
110 -300 keV CONTINUUM FLUX (10^{-2} ph/cm^2-s)
0
0.5
1.0
1.5
2.0
2.5
511 keV LINE FLUX (10^{-3} ph/cm^2-s)
0
0.5
1.0
1.5
2.0
2.5
3.0

FIGURE 2