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ABSTRACT

We demonstrate that the X-ray flux from 2A0311-227 is modulated at the 81 min orbital period of its optical counterpart. An absorption dip with $N_H \sim$ [illegible] $\times 10^{22}$ H atoms cm^{-2} is observed at magnetic phase 0.42 that we interpret as the accretion column of a magnetic white dwarf passing in front of the X-ray source. The spectrum is thermal with a temperature of 18 keV and a 300 eV equivalent width iron line at 6.6 keV.

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I. INTRODUCTION

Photometric, spectroscopic and polarization measurements of the optical counterpart of 2A0311-227 have established that this source is in 81 min binary system similar to AM Her (Boley, Johns and Maker 1979; Griffiths et al. 1979). The salient features of this star can be summarized as follows:

A linear polarization pulse is seen every 81 mins that has been used to define the binary phase ($\phi_{0.0}$, Tapia 1979) . Circular polarization is seen that varies with the 81 min period from 15 to -2.5% with zero occurring at $\phi_{0.9}$ and $\phi_{0.0}$, with perhaps some evidence for variability in the minimum value (Tapia 1979; Bailey, Hough and Axon 1980). A smooth infrared modulation reaches maximum at ~ $\phi_{0.5}$ and minimum at ~ $\phi_{0.8}$ with in addition a sharp eclipse like dip at ~ $\phi_{0.42}$ (Ward et al. 1979; Bailey et al. 1980). In the visual the modulation is double peaked with maxima at $\phi_{0.6}$ and $\phi_{0.0}$ (Bond, Chanmugan and Grauer 1979; Verbunt et al. 1980; Watson, Mayo and King 1980). By the U band the modulation is again single with minimum at ~ $\phi_{0.55}$ (Verbunt et al. 1980). Sinusoidal radial velocity variations in the H and He lines are seen with maximum velocity away from the observer occurring at $\phi_{0.5}$ (Williams et al. 1979; Schneider and Young 1980; Verbunt et al. 1980). Between $\phi_{0.4}$ and $\phi_{0.55}$ the Hα and HeI 5876/6678 lines change from emission to absorption. Lastly, Patterson (1980) has communicated to us that the soft X-ray flux of this source undergoes eclipses every 81 mins.

Because of the similarity of these properties to those of AM Her the magnetically phase locked white dwarf model (see Joss, Katz and Rappaport 1979 and ref. therein) has been adapted to explain the observed features of 2A0311-227. We have made observations, first reported in White et al. (1980), that show the X-ray flux of this source is modulated with the 81 minute period and that the eclipses are the result of absorption events. This result is presented here along with a discussion as to the probable geometry of this system.

II. OBSERVATIONS

Two sets of observations are reported that utilized the HEAO 1 and Einstein observatories. They were complicated because 2A0311-227 has a binary period of 81 mins that is very close to the 95 minute orbital period of the satellites. Earth occultation and regions of high charged particle background restricted observations to an average of ~ 40% per satellite orbit. So to obtain complete coverage of one 81 min binary cycle we had to observe for at least a 5 hour interval. The HEAO A2+ experiment (Rothschild et al. 1980)

+The A2 experiment on HEAO-1 is a collaborative effort led by E. Boldt of GSFC and G. Garmire of CIT, with collaborators at GSFC, CIT, JPL and UCB.

made a 6 hour pointed observation on 1978 July 19. The two detectors used were sensitive in the 2-30 keV (MED) and 2-60 (HED) energy bands. The 0.5 to 4.5 keV Solid State Spectrometer (SSS, Joyce et al. 1980) and 2-20 keV Monitor Proportional Counter (MPC) on Einstein obtained 4 hrs. of data spread out over 2 days starting on 1979 July 15.

III. PERIODICITIES

The data were searched for the 81 min period using Fourier analysis techniques and in each case it was detected at > 99% confidence. Figures 1 and 2 show the data folded into a variety of energy bands using the following ephemeris:

$$T_{LPMAX} = JD2444131.6751+0.0562660E$$

This uses the epoch given by the linear polarization pulse and the period from the IR data (Bailey et al. 1980). Both sets of data are modulated with a similar broad maximum centered about $\phi_{0.5}$ and a peak to mean amplitude of ~ 40%. This modulation is perturbed in two ways. First there is for both at $\phi_{0.42}$ a dip of duration ~ 0.07 in phase (~ 6 mins) which becomes much more pronounced at lower energies, suggesting it results from an absorption event. This is probably the cause of the eclipses reported by Patterson (1980) because at low energies the flux becomes zero (Figure 2). Secondly there are flares in the Einstein data at $\sim\phi_{0.4}$ and possibly $\sim\phi_{0.2}$ on a timescale of order 5-10 mins. The evidence we have suggest that these flares are single events that do not persist at the same binary phase from cycle to cycle. However because of the afore mentioned sampling problem we cannot completely rule out phase related behavior.

The data were searched for regular pulsations and none were found greater than 10% between 160 ms and ~ 5 min. However, while there was no evidence for a coherent periodicity, there was excess power ~ 10% above the expected statistical noise for periods between 5 and 10 minutes, i.e. the timescale of the flaring behavior.

IV. SPECTRUM

The PHA data from the SSS, MED and HED were fit to the standard spectral models. The MED and HED were consistent with either a 2.0 photon index power law or an ~ 18 keV thermal model. The SSS only fit a thermal model with kT > 7 keV or a flat 1.0 photon index power law. If we assume no spectral variability between the two observations then we conclude that a thermal fit of 18 keV is the correct model. In addition the MED data required a line at 6.6 keV with an equivalent width of ~ 300 eV. This is consistant with the expected line emission from a plasma in thermal equilibrium. The photon spectrum obtained using the best fit parameters given in Table 1 is shown in

Figure 3 for all three detectors.

Apart from the absorption dip at $\phi_{0.42}$ there was little evidence for any gross spectral variability across the 81 min modulation, although we did note some marginal evidence for a softening of the spectrum between $\phi_{0.6}$ and $\phi_{0.8}$. Because the source is weak we cannot usefully use the PHA data to define the spectrum during the dip. However if we assume the underlying spectrum is constant then the ratio of the counts in the MED and HED gives an N_H during the dip of $(5\pm4) \times 10^{22}$ H atoms cm^{-2}. A similar value is obtained from the SSS/MPC data.

V. DISCUSSION

Comparison of the X-ray properties of 2A0311-227 with those in other wavebands reveals the following:

1. The overall shape and depth of modulation in the X-ray and IR are remarkably similar (Bailey et al. 1980), suggesting a common origin.
2. The maximum in the X-ray (and IR) occurs at the maximum of circular polarization and 180^{o} out of phase with the linear polarization pulse (Tapia 1979; Bailey et al. 1980).
3. The X-ray, IR and some of the optical emission lines go into absorption around $\phi_{0.42}$ (Verbunt et al. 1980). The optical event lasts about three times longer than the IR and X-ray. The IR dip is similar in duration to the X-ray and occurs at about the same phase, though Bailey et al. (1980) note "the narrow (IR) minimum seems to be slightly variable in phase and depth from cycle to cycle".
4. There is flaring (flickering) in all wavebands on a timescale of ~ several minutes.

It is widely believed that AM Her is an accreting magnetic white dwarf that corotates with its orbital period (see Chiapetti, Tanzi and Treves and refs. therein). The similarities of the properties of 2A0311-227 to those of AM Her has lead people to adapt this model to explain 2A0311-227 (Verbunt et al. 1980; Schneider and Young 1980; Watson et al. 1980; Bond et al. 1979). The X-ray properties of 2A0311-227 of a high temperature spectrum and short timescale flickering supports this view. We note one curious difference that the iron line emission of 2A0311-227 has an equivalent width a factor 5 lower than AM Her. The interpretation of these X-ray properties has been discussed with regard to AM Her (e.g. Tuohy et al. 1980 and refs. therein) and will not be repeated here.

The coincidence of the absorption events in the optical line emission, the IR flux and the X-ray flux strongly suggests they are all caused by a common body of material. Because the optical lines redward of 5500 Å go into absorption during this event the material must itself be responsible for the line emission. Verbunt et al. (1980) position the emission lines in the gas stream close to the companion star and explain the U band minimum at $\phi_o \sim 0.4$ as a self occultation by the white dwarf, pointing the active pole away from the companion. However, because we will be looking across the gas stream, the expected column density will be many orders of magnitude below that observed. Also, this geometry incorrectly predicts an X-ray minimum of $\phi_{0.4}$. Watson et al. (1980) require the dip to be the result of an occultation by the atmosphere of the companion star, which in turn means the emission lines originate from the stars atmosphere. This conflicts with the result of Schneider and Young (1980) who show the velocities of the lines infer that they are formed in material falling freely onto the white dwarf.

We suggest that the X-ray absorption event is caused by the accretion column at the magnetic pole of the white dwarf passing through our line of sight. A large part of the IR and optical flux probably comes from the cyclotron radiation of a high temperature plasma contained in a 10^6-10^8 G magnetic field (e.g. Lamb and Masters 1980). The linear polarization pulse occurs when the field lines are perpendicular to the observer and the Faraday effect is minimal (Stockman 1977). Conversly the maximum of the circular polarization will occur when we are viewing along the field lines. This provides a natural explanation for the IR and X-ray modulations as a $\cos\theta$ effect (Basko and Syunyaev 1976) i.e. during the linear polarization pulse we are viewing at an oblique angle to the emission region and hence see a minimum. For the accretion column to get in the way in the observed manner the system inclination must be to first order $\sim 45^\circ$, with a similar declination for the magnetic pole. Thus 180° after the polarization pulse we will view directly along the magnetic dipole. We can make an order of magnitude calculation for the expected absorption in the column. The radius A of the column must increase with height R above the star and for a magnetic dipole A will be approximately proportional to $R^{1.5}$. Because of this 90% of the X-ray absorption will occur within three stellar radi of the white dwarf. The duration of the dip yields a radius for the accretion column at its base of ~ 800 km. An X-ray luminosity of 10^{32} ergs s^{-1} gives an $\dot{M}$ of 10^{-13} M_o yr^{-1} and integrating out along the column predicts a column density of about 2×10^{22} H atoms cm^{-2}, similar to our observed value. The optical event is three times longer than the X-ray which indicates the optical emission comes from higher up in the column (~ 0.3 R_o). The lack of any major phase lag between the three absorption events suggests that the column and hence the pole to first order points towards the companion star. As the U band variations probably arise from X-ray heating of the companion, then the fact that they are in anti-phase with the IR supports this orientation.

Clearly this model is only a "bare bones" description of the system to account for the gross properties. For instance some sort of asymmetry is inferred by the fact that the absorption dip occurs slightly earlier in phase than the expected $\phi_{0.5}$. Also, much more detailed modelling will be required to explain the complexities of the visual light curve. Nonetheless we are fortunate that nature has aligned things such that the accretion column passes in front of the X-ray source. Future measurements of 2A0311-227 will be able to utilize this as a probe to deconvolve the location of the various emission regions and to build up a better understanding of the accretion column itself.

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TABLE 1: 2A0311-227 THERMAL FITS

	SSS	MED	HED	
Normalization	0.0024±0.0005	0.0044±0.0005	0.0036±0.0005	
kT	18.0 (Fixed)	$13.3^{+10.0}_{-2.0}$	18.1±3.0	keV
N_H	$(1.0\pm0.5)\times10^{21}$	$(6\pm5)\times10^{21}$	$<10^{22}$	H atoms cm^{-2}
Line				
Flux	----	$(1.0\pm0.5)\times10^{-4}$	----	ph $cm^{-2}s^{-1}$
Width	----	<2	----	keV
Energy	----	6.6±0.2	----	keV
EW	----	293^{+300}_{-140}	<400	eV
χ^2_r	1.6	1.4	1.3	

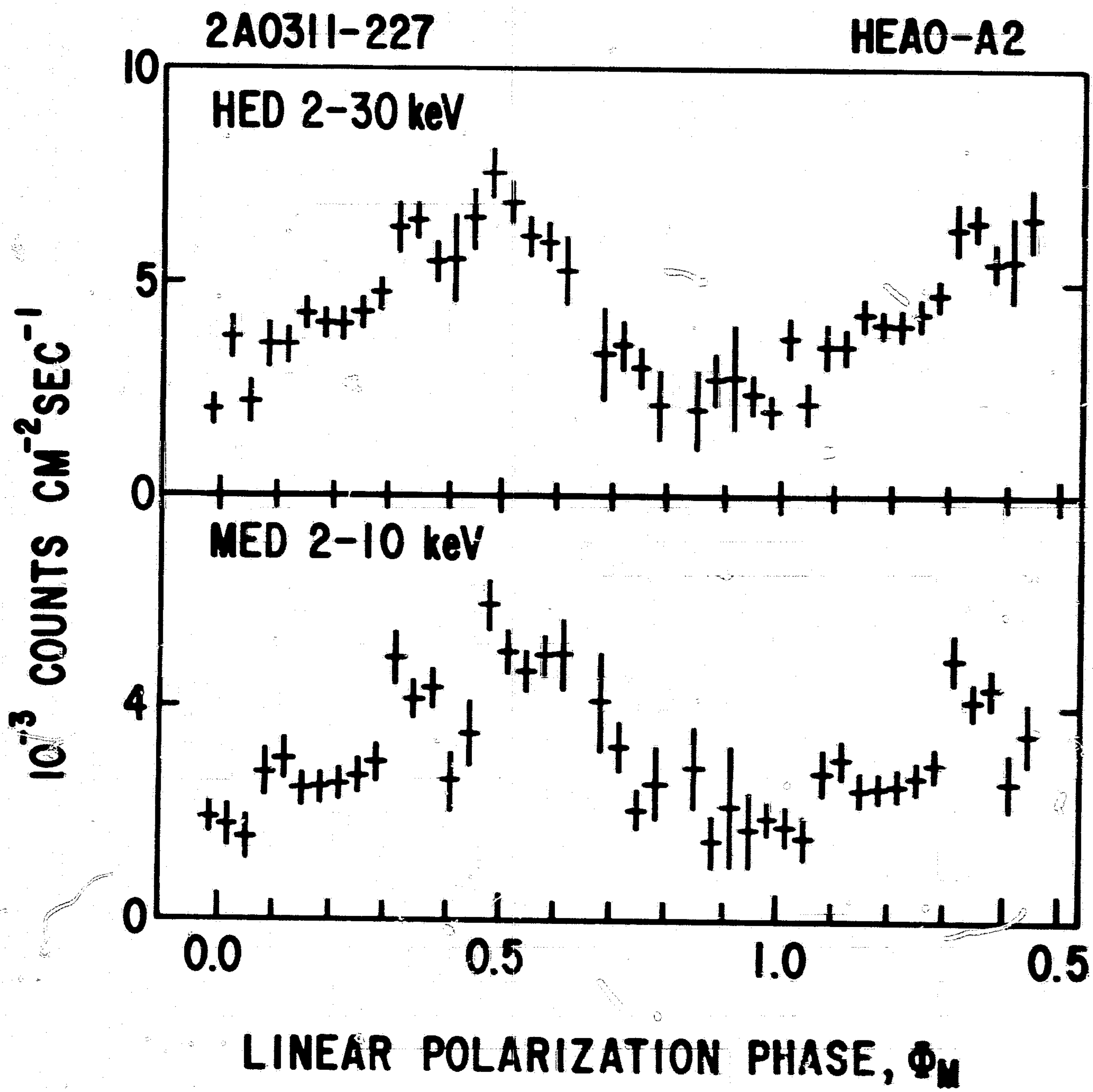
$$L_{x(0.5-60\ keV)} = 1.7 \times 10^{32} \times \left(\frac{d}{100pc}\right)^2 \text{ ergs s}^{-1}$$

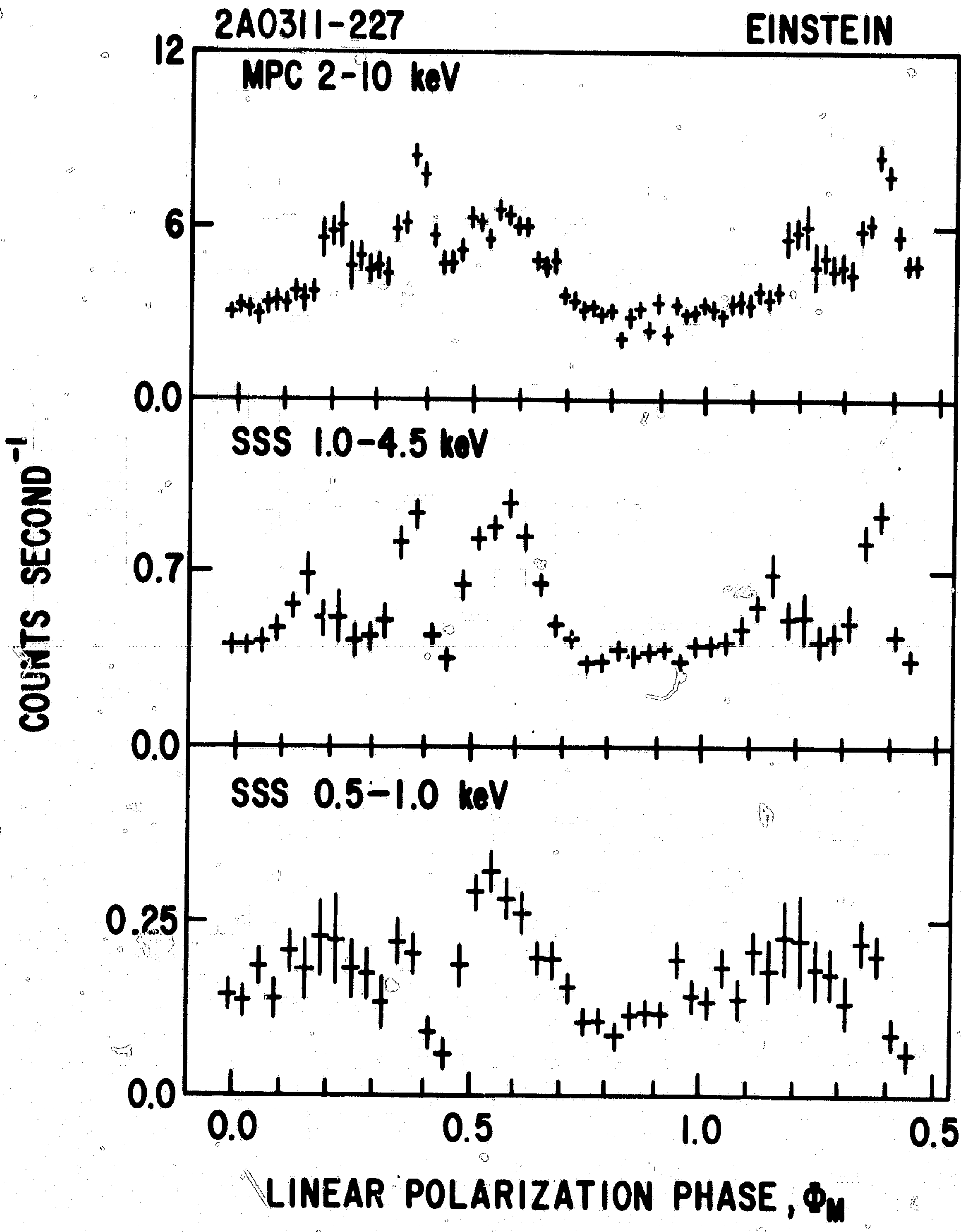
FIGURE CAPTIONS

Figure 1 - The HEAO A2 data folded about the 81 min ephemeris given in the text. The plot is repeated for half a cycle for clarity.

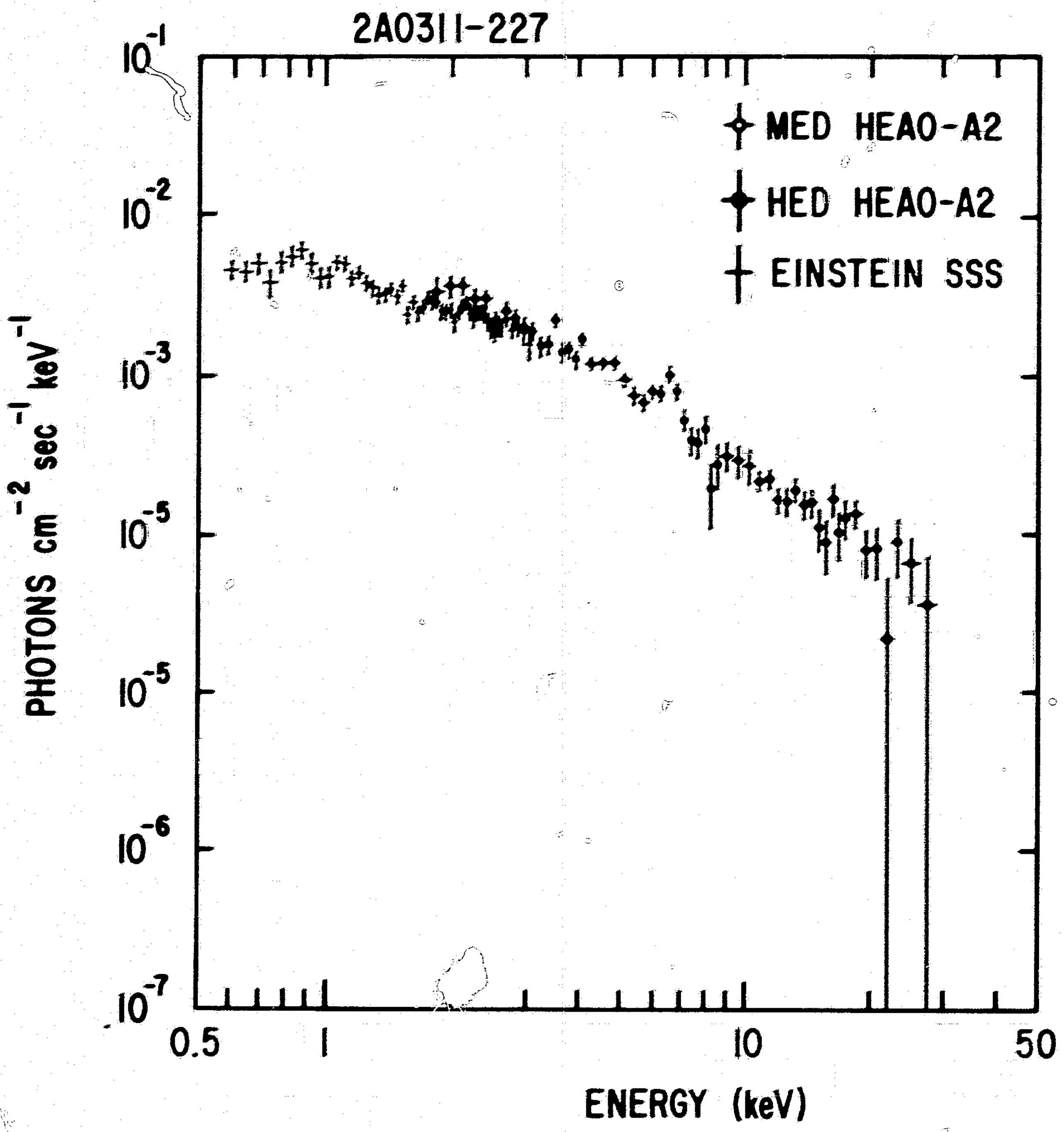
Figure 2 - The SSS/MPC data folded in a similar manner to Figure 1.

Figure 3 - The photon spectrum of 2A0311-227 from the SSS, MED and HED. The parameters given in Table 1 were assumed during the deconvolution.


2A0311-227
HEAO-A2
HED 2-30 keV
MED 2-10 keV
10
5
0
4
0
0.0
0.5
1.0
0.5
10^{-3} COUNTS $CM^{-2}SEC^{-1}$
LINEAR POLARIZATION PHASE, Φ_M



2A0311-227
EINSTEIN
MPC 2-10 keV
SSS 1.0-4.5 keV
SSS 0.5-1.0 keV
COUNTS SECOND^{-1}
12
6
0.0
0.7
0.0
0.25
0.0
0.0
0.5
1.0
0.5
LINEAR POLARIZATION PHASE, Φ_M


2A0311-227
MED HEAO-A2
HED HEAO-A2
EINSTEIN SSS
PHOTONS cm^-2 sec^-1 keV^-1
10^-1
10^-2
10^-3
10^-5
10^-5
10^-6
10^-7
0.5
1
10
50
ENERGY (keV)