(NASA-TM-83839) THE DISCOVERY OF 50 MINUTE PERIODIC ABSORPTION EVENTS FROM 4U1915-05 (NASA) 18 p HC A02/MF A01 CSCL 03B
N82-15001
Unclas
G3/90 04836

NASA

Technical Memorandum 83839

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OCTOBER 1981

National Aeronautics and
Space Administration

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THE DISCOVERY OF 50 MINUTE PERIODIC ABSORPTION EVENTS FROM 4U1915-05

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ABSTRACT

We demonstrate that the steady flux from 4U1915-05 undergoes periodic absorption dips with a period of 50 minutes. This period most likely represents the underlying orbital period of the system. Variations in the depth and duration of these events suggests that they are caused by a bulge in the edge of the accretion disk, at the point where the gas stream impacts the disk. The mass losing star in this system is probably a low mass white dwarf. The spectrum of the dips indicates that the metallicity of the absorbing material is at least a factor 17 below solar values.

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I. INTRODUCTION

The most promising model for Type I X-ray bursts is thermonuclear flashes on the surface of an accreting neutron star (e.g. Joss 1980). The accreted material probably comes from a binary companion but, to date, eclipses have not been seen in the steady flux from any of the 30 or so known X-ray burst sources (Cominsky et al. 1980). Milgrom (1978) has suggested that this is because a thick rim around the edge of the accretion disk shadows the companion in the high inclination systems and prevents eclipses being seen. Two transient X-ray burst sources, Cen X-4 and Aql X-1 (Matsuoka et al. 1980; Koyama et al. 1981), have on occasions exhibited sinusoidal like modulations with periods of 8 hours and 1.3 days respectively (Kaluzienski, Holt and Swank 1980; Watson 1976). While the nature of these modulations is unclear, the detection of stellar spectra from the optical counterparts of these two transients in quiescence has provided circumstantial evidence for binarity (van Paradijs et al. 1980; Thorstensen, Charles and Bowyer 1978).

We present extensive observations of 4U1915-05/MXB1916-05 (Becker et al. 1977; Lewin, Hoffman and Doty 1977) where we detect absorption dips recurrent with a 50 min period. Walter et al. (1982) have independently discovered these events (as first reported jointly in Walter, White and Swank 1981). This is the first coherent periodic phenomenon to be found in one of the "steady" burst sources.

II. THE ABSORPTION DIPS

4U1915-05 was observed by the HEAO 2 Einstein Solid State Spectrometer (0.5-4.5 keV; SSS) and Monitor Proportional Counter (1.5-10 keV; MPC) on 1979 April 24 for two consecutive satellite orbits. In each orbit the steady flux was seen to undergo an erratic reduction in flux lasting ~ 10 min, with the start of the two events separated by 100 min. More extensive OSO-8 X-ray observations made between 1976 April 12-13 and 1978 April 8-13 were searched for a similar phenomenon and it was immediately clear that the dips are periodic with a period of ~ 50 min. The shorter period was not apparent in the SSS observation because the orbital period of the Einstein observatory was 97 min and for ~ 50% of the orbit the source was occulted by the earth. The longer observing time of the OSO-8 observations allowed the sampling window to drift over half a day which removed the ambiguity between 50 and 100 min. In Figure 1 the SSS and MPC data are shown, folded on a period of 50.05 min with a time resolution of 20s. The flux does not drop to zero and the MPC hardness ratio indicates a marked hardening of the spectrum, suggestive of absorption events.

The OSO-8 observations allow the evolution of the dips to be followed over several days. In Figure 2 the data from the 1978 observation is grouped into half day blocks and folded with a period of 50.05 min, for a constant but arbitrary epoch. The dips evolve with time. On days 99.0 and 99.5 they are clearly seen at about phase 0.0, but they fade on day 100.0 and by day 100.5 all activity has ceased. The dips re-appear on day 101.0 along with a series of anomalous dips 180^{0} out of phase with the primary events. The anomalous dips are less deep absorption events that disappear after half a day. The phase of the primary dips then drifts backwards with associated changes in the structure and depth of the events. The April 1976 observation (not shown) spans two days and strong dips are apparent for the last 1.5 days. In this case there was no evidence for any phase drift from the 50.05 min period, or for any anomalous dips. Absorption dips recurrent with a 50 min period were also evident in an Oct 1976 observation, which was however subject to source confusion, and a 6 hr HEAO-1 A2 pointed observation made in Oct 1978, although in this case the dips were very shallow. The source was burst active throughout the OSO-8 and HEAO-1 A2 observations. There was no obvious correlation between the bursts and the absorption dips.

The period of the dips is difficult to determine because of the phase jitter. If the primary dip is kept in phase over the whole 5 day interval in April 1978, and the local phase drifts attributed to changes in the structure of the dips, then the period is 50.06 ± 0.03 min. The drift in phase from days 101.5-103.0 indicates a slightly shorter period of 49.93 ± 0.06 min. The period cannot be determined acc rately enough from a single observation to give a meaningful ephemeris for the three years of observations.

III. THE SPECTRUM

The reduction in flux at 10 keV measured by the MPC for the deepest events is ~ 50% which, using the photo-electric absorption cross-sections from Fireman (1974) plus the Thomson scattering cross-section, gives an equivalent hydrogen column density of ~ 4 x 10^{23} H cm^{-2}. Absorption by such a large amount of cold material would completely surpress the source below 3 keV; however, Figure 1 shows that the SSS count rate did not vanish. OSO-8 spectra taken during the dips also cannot be explained just by absorption in cool material with solar abundances. In Figure 3 the non-dip incident spectrum is shown together with the summed dip spectrum taken from only the part of the dips where the 2 min average count rate was less than half the unperturbed flux (the data used showed no evidence for extreme changes in absorption on timescales between 10s and 2 min). While there is a slight turnover in the dip spectrum corresponding to ~ 5 x 10^{22} H cm^2, the majority of the dip is caused by an overall energy independent 50% reduction in flux. If the absorbing medium is partially ionized an upper limit to any edge at 7-9 keV implies that either iron is fully ionized or its abundance is less than 1/4 solar. A cold medium gives a good fit to the data if the metals are underabundant by a factor of 30, with a 90% confidence limit of a factor of 17.

The non-dip continuum measured with HEAO-1 A2 and OSO-8 was variable. The OSO-8 data can be fit with a power law with the energy index varying between 0.5 and 0.7. Thermal bremsstrahlung models gave best fit kT $\sim$ 25-35 keV. During the HEAO-1 A2 observation the spectrum appeared slightly steeper, and was better fit with a bremsstrahlung kT = 12 ± 2 keV. The best value of the hydrogen column density, $(3.0 \pm 0.5) \times 10^{21}$ H cm^{-2} comes from the SSS and is within a factor 2 of the expected interstellar absorption (Baker and Butler 1975; Bohlin, Savage, and Drake 1978). Becker et al. (1977) found evidence for an absorption edge at 9.1 keV; however, re-analysis of these data show that this was an artifact caused by a combination of summing the dip and non-dip spectra, plus uncertainties in the background above 10 keV. The total 0.5-60 keV flux remained relatively steady at 1.0-1.3 x 10^{-9} ergs cm^{-2}s^{-1} which for an isotropic source corresponds to an apparent luminosity of 1.2-1.5 x 10^{37}(d/10 kpc) ergs s^{-1}.

IV. DISCUSSION

The 50 min period appears to be relatively stable over many years which suggests that the underlying clock is binary orbital motion. If we assume the standard X-ray binary model of a neutron star primary accreting material from a Roche limited secondary, then the mass of the secondary M_S, for a given Roche radius, is independent of the mass of the primary M_X when $M_S/M_X < 0.8$, and is given by $M_S = 79\ (R_S/R_0)^3\ P^{-2}\ M_0$, where P is the orbital period in hours (e.g. Faulkner, Flannery and Warner 1972). Combining this with the mass-radius relation for a hydrogen ZAMS star, given by Whyte and Eggleton (1980), does not give a valid solution above the minimum mass of 0.085 M_0 for hydrogen burning. A ZAMS helium star would, at 10 kpc, be a very blue $\sim$ 14th mag star, which is ruled out by the lack of such a star in the error circle (Bowyer, Clarke and Henry 1981; Walter et al. 1981). If the secondary is degenerate, then the mass-radius relation calculated by Vila (1971) for degenerate stars yields masses of 0.009 M_0 and 0.04 M_0 for helium and hydrogen (X=0.75) white dwarfs respectively. Thus, while there remain uncertainties in the mass-radius relation at the low mass end of the hydrogen ZAMS, the simplest solution is a degenerate secondary. In a subsequent paper constraints on the composition of the secondary and the mass transfer rate provided by the X-ray bursts will be discussed (Swank, Taam and White 1982).

The phase jitter and variable depth of the primary dips, plus the presence of the anomalous dips, rules out a partial occultation by the atmosphere of the companion. For a gas stream to cause the dips, the lack of any eclipse by the secondary means the stream must be well out of the orbital plane. Magnetic funnelling of the material could be responsible for this, however the erratic nature of the dips argues against the association of the period with the rotation of a neutron star.

Recent evidence has suggested that at the point where the inflowing gas stream collides with the disk (the "bright spot" seen in cataclysmic variables) there is considerable turbulence that causes the disk to swell in the vicinity of the confluence (White and Holt 1982; White et al. 1981; Mason et al. 1980; Chester 1979; Alpar 1979; Lubow and Shu 1976). The angle above the orbital plane subtended to the X-ray source by this structure may exceed that of the companion. The turbulence provides a natural explanation for the dramatic variations seen within individual dips and from dip to dip. The variable depths of the dips, the phase jitter and the anomalous dips all probably reflect long term changes and instabilities in the outer structure of the disk. These instabilities are not understood, but other observations indicate that they are important (e.g. Robinson, Nather and Patterson 1979), in particular there is evidence for a second smaller bulge in the disk, opposite the one at the confluence, that may be responsible for the anomalous dips (White and Holt 1982).

A number of absorption dips have also been seen from another X-ray burst source MXB1659-29, although the data were insufficient to establish a period (Lewin 1979; Cominsky 1981). Cominsky (1981) has interpreted these dips in terms of blobs of material orbiting the outer regions of the disk occulting the central X-ray source. If we apply this model to 4U1915-05, the 50 min period then represents the Keplerian period of the disk's outer regions. However in this case it is very difficult to understand how a blob that spans at least 20% of the rim can maintain its integrity over several days. Also, Figure 2 indicates that after a blob disperses on day 100.5, a mechanism must be found to force the next blob to reappear at the same phase. This behavior is more easily reconciled with structure in the disk that is fixed with respect to the two binary components.

The absence of any eclipse by the secondary gives $i \lesssim 86^{\circ}$ for a helium white dwarf and $i \lesssim 81^{\circ}$ for a hydrogen white dwarf. If we assume the disk fills two thirds of its Roche radius then the peak bulge height must be respectively $\gtrsim 6\%$ and $\gtrsim 12\%$ the radius of the disk. The maximum duration of the events indicates the bulge extends at least 70° around the disk. If the disk fills two thirds of its Roche radius then the ~ 2 min characteristic timescale of the flickering within the second dip shown in Figure 1 gives a characteristic clumping size of $\sim 3 \times 10^{9}$ cm.

If we assume that there are no large changes in absorption on timescales of $\lesssim 1$ s and that the size of the occulting material is much greater than the X-ray source, then the relative energy independence of the dips above 3 keV can be understood if the photo-electric absorption by the high Z elements has been inhibited, either by photo-ionization or by a reduction in the metallicity of the absorbing medium. It is difficult to obtain ~ 10^{24} H cm^{-2} of fully ionized material at ~ 10^{10} cm from steady source of luminosity ~ 10^{37} ergs s^{-1} (assuming the bursts are near the Eddington limit). The simplest explanation for the dip spectrum is an underabundance of the metals, consistent with a population II secondary (Kraft 1979). An underabundance could also be caused by sedimentation of the heavy elements in the white dwarf secondary, although it is unclear that this process is very effective for such a low mass white dwarf (e.g. Vauclair 1979). A population II secondary would be in agreement with the population II galactic distribution of X-ray bursters.

There are three other binaries with periods less than ~ 80 min: HZ29 (19 min; Faulkner, Flannery and Warner 1972); G61-29 (47 min; Nather, Robinson and Stover 1981) and 4U1626-67 (42 min, Middleditch et al. 1981). The first two contain white dwarf primaries, and the presence of only Helium lines in the optical spectra and the absolute magnitudes indicate that in both the secondary is a helium white dwarf. The same arguments that suggest a degenerate secondary in 4U1915-05 are also valid for the 7s X-ray pulsar 4U1626-67. The origin of these interacting twin-degenerate binaries is problematic. The binary period of a Roche limited secondary losing mass to a degenerate primary will decrease until the mass transfer occurs on a Kelvin-Helmholtz timescale, where upon the orbital period reaches a minimum and then increases again, with the secondary now degenerate (Paczynski and Sienkiewicz 1981; Rappaport, Joss and Webbink 1981) The value of this minimum period is model dependent, but for the hydrogen ZAMS it is around 60-80 min. Shorter orbital periods, helium degenerate secondaries, and neutron star primaries require substantial modifications to this evolutionary scenario. Common envelope evolution is the most likely progenitor to cataclysmic variables (e.g. Paczynski 197[illegible]) and it is conceivable that this process has lead directly to the formation of twin-degenerate configurations. However, specific evolutionary tracks leading to the observed systems, within reasonable timescales, have not yet been identified.

The discovery of a 50 min binary period from 4U1915-05 confirms the earlier hints and suspicions that X-ray burst sources are in binary systems. While the companion in the systems with extremely high inclinations may be completely shadowed by a rim at the edge of the accretion disk, as suggested by Milgrom (1978), 4U1915-05 demonstrates that for somewhat lower inclinations perturbations in the disk thickness can occult the X-ray source. For sources close to the Eddington limit the presence of an optically thick accretion disk corona will smear out these absorption dips into a Cyg X-3 like modulation (White and Holt 1982). However for the lower luminosity sources, absorption dips caused by the outer disk structure must be present at a limited range of inclination (probably of order 70-80°).

We would like to thank the participants of the UCSC 1981 Summer Workshop on "Cataclysmic Variables and Related Systems", in particular Ron Taam, for many stimulating talks and discussions.

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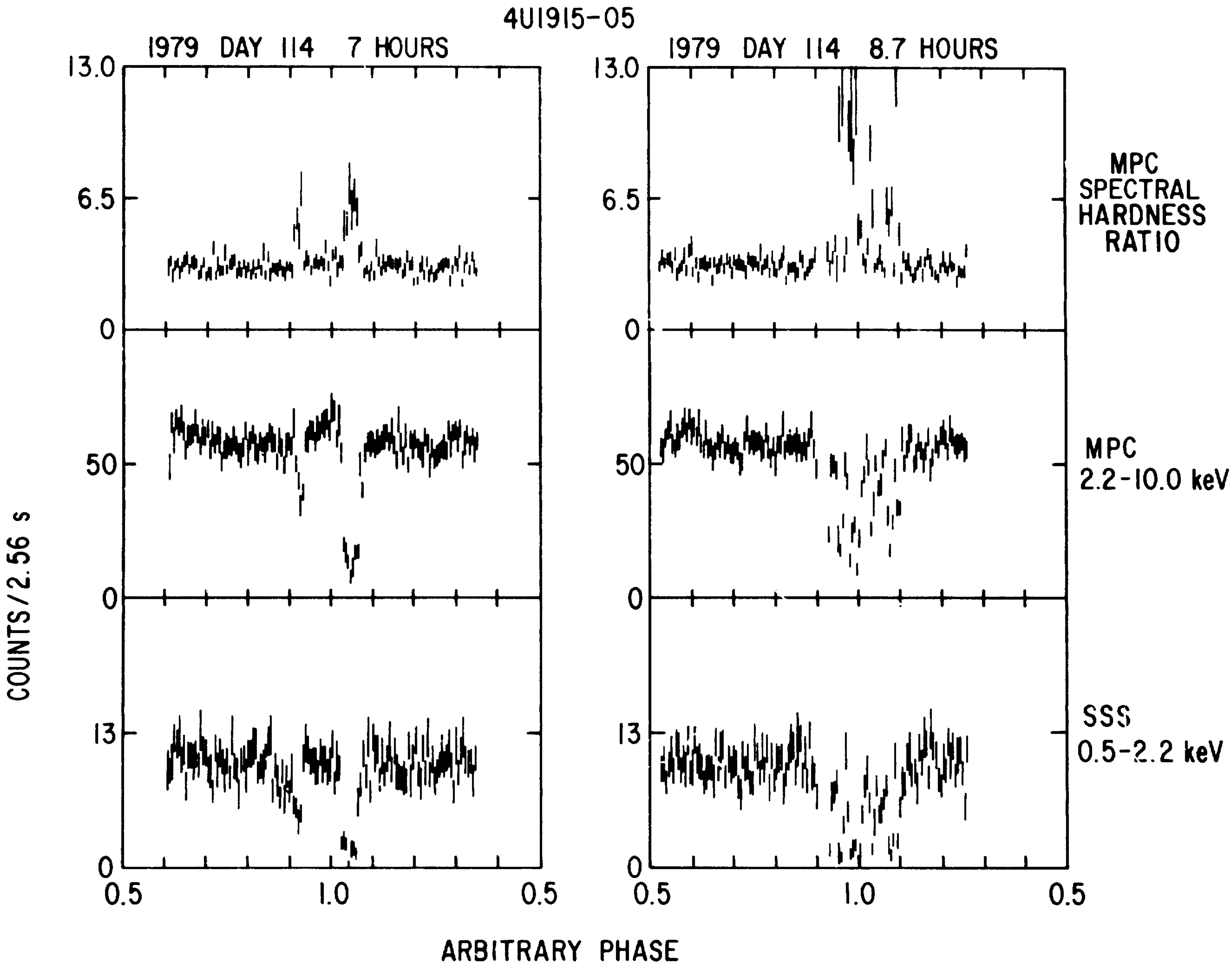
FIGURE CAPTIONS

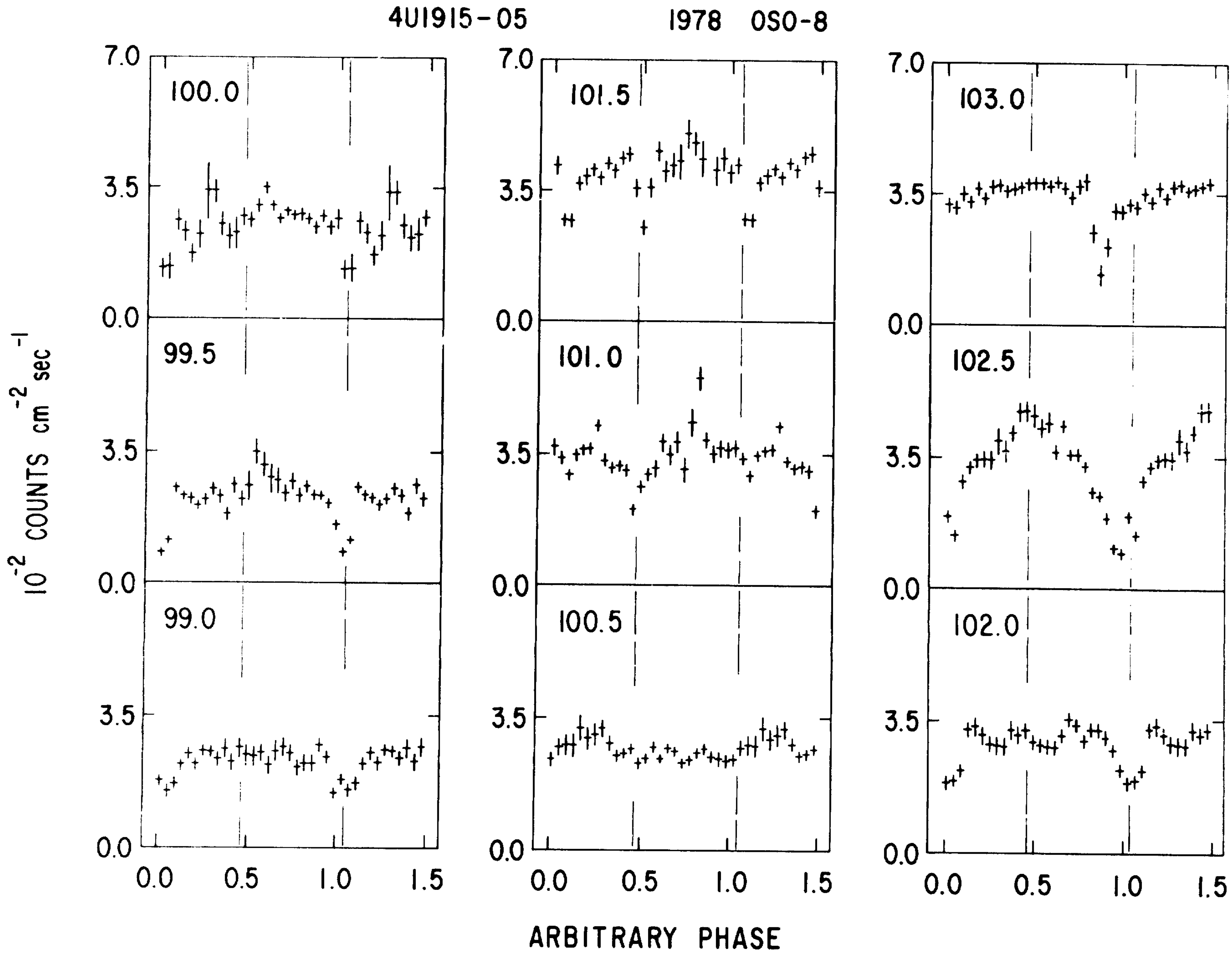
Figure 1 - Two subsequent orbits of SSS and MPC data folded over a period of 50.05 min with a time resolution of 20s and binned into two non-over lapping energy bands. The epoch is arbitrarily taken for each as 1979 day 113.9965 The MPC spectral hardness ratio is the count rate in the energy band 3-10 keV divided by that in 1-3 keV.

Figure 2 - A five day OSO-8 observation folded with an arbitrary epoch of 1978 day 98.009 and a period of 50.05 min. Each panel represents half a day of data with each plot is repeated for half a cycle for clarity. The first day of data from day 98 is not shown, but is similar to that on day 99.

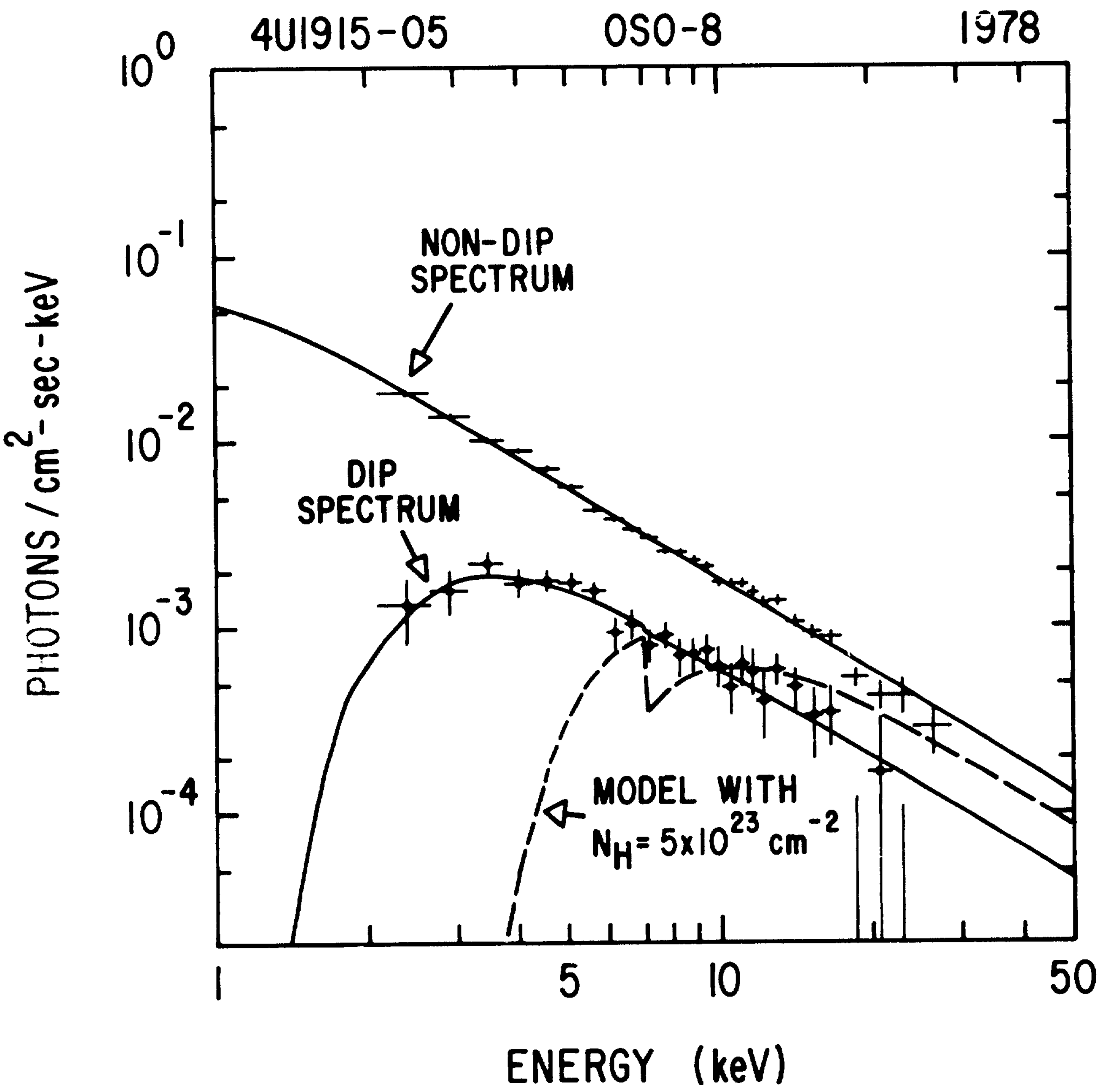
Figure 3 - The incident spectrum, from OSO-8 observations in April 1978, for the sum of both the dip and non-dip data. An intensity filter was used to differentiate between dip and non-dip. A power law with energy index $\alpha = 0.67$ is shown for the non-dip spectrum. The best fit dip spectrum includes 5×10^{22} H cm^{-2} of absorption plus an overall reduction in flux corresponding to 10^{24} H cm^{-2} of hot material.



4U1915-05
1979 DAY 114 7 HOURS
1979 DAY 114 8.7 HOURS
13.0
6.5
0
50
0
13
0
MPC SPECTRAL HARDNESS RATIO
MPC 2.2-10.0 keV
SSS 0.5-2.2 keV
COUNTS/2.56 s
0.5
1.0
0.5
ARBITRARY PHASE



4U1915-05
1978 OSO-8
100.0
99.5
99.0
101.5
101.0
100.5
103.0
102.5
102.0
7.0
3.5
0.0
0.0
0.5
1.0
1.5
ARBITRARY PHASE
10^{-2} COUNTS cm^{-2} sec^{-1}


4U1915-05
OSO-8
1978
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
PHOTONS / cm^2 - sec - keV
NON-DIP SPECTRUM
DIP SPECTRUM
MODEL WITH $N_H = 5 \times 10^{23}\ cm^{-2}$
1
5
10
50
ENERGY (keV)

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