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SPECTRAL CHARACTERISTICS OF 3U 1915−05, A BURST SOURCE CANDIDATE

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ABSTRACT

An X-ray burst source has been discovered near the X-ray source 3U 1915−05. The continuum spectra of both the burst source and the quiescent source 3U 1915−05 are hard, with kT for thermal bremsstrahlung models above 20 keV. The spectrum of 3U 1915−05 has a feature at 9.1 keV, which, if attributed to absorption by hydrogen and helium-like iron, suggests the presence of a highly ionized cloud surrounding a central X-ray source.
Subject headings: X-rays: bursts — X-rays: spectra

I. INTRODUCTION

During the period 1976 April 11–14, the X-ray source 3U 1915−05 was observed by the GSFC Cosmic X-ray Spectroscopy experiment on OSO-8. During these three days, a series of 11 bursts were observed from the region containing 3U 1915−05. In the last year, ~25 such burst sources have been discovered (Lewin *et al.* 1977*a*). To date, at least five of these burst sources have been identified with "steady" sources of X-ray emission (Lewin 1976; Lewin *et al.* 1977*b*). This *Letter* will report on the spectra and light curves for both 3U 1915−05 and the burst source and will discuss the possibility that they are one and the same source.

II. OBSERVATIONS

The observations were made by a xenon-filled proportional counter with a 5° circular field of view. The detector is occulted 4 times each satellite revolution by the pointed solar instruments and by occultation shields. Counting rates are obtained every 0.160 s while spectral histograms are accumulated every 40 s. A description of the experiment is given by Pravdo *et al.* (1976).

The data indicated that a continuous X-ray source was within the field of view of the detector, which we attribute to the only known source within the field of view during this period, 3U 1915−05. The observed X-ray intensity from 3U 1915−05 was highly variable, changing by as much as a factor of 3 within 5000–10,000 s. The existence of these rapid variations does not depend on the assumed location of the source because the orientation of the detector was changing little over such time intervals. The average intensity of 3U 1915−05 during the observation was $10.0 \pm 0.6 \times 10^{-11}$ ergs cm^{-2} s^{-1} between 2 and 6 keV and 28.5×10^{-11} ergs cm^{-2} s^{-1} between 2 and 20 keV. *Uhuru* detected a varying intensity for 3U 1915−05 with a range between 8 and 40×10^{-11} ergs cm^{-2} s^{-1} (Giacconi *et al.* 1974). The average spectrum of 3U 1915−05 is shown in Figure 1.

Attempts to fit the spectra of 3U 1915−05 with simple power law and thermal bremsstrahlung models did not result in acceptable χ^2 values (45 for 15 degrees of freedom). However, the inclusion of an absorption edge at 9.1 ± 0.4 keV in either model resulted in acceptable fits. This feature is significant at the 5 σ level. The edge was represented by the analytic form

$$\exp\left[-(y/E)^{+3}\right] \text{ for } E \geq E_{\text{EDGE}} ,$$

and by unity for $E < E_{\text{EDGE}}$. The best fit power-law is $\alpha = 1.60 \pm 0.15$ and $N_{\text{H}} = 2.5$ $(+1.5, -1.2) \times 10^{22}$ atoms cm^{-2} with $\chi^2 = 16.8$ for 13 degrees of

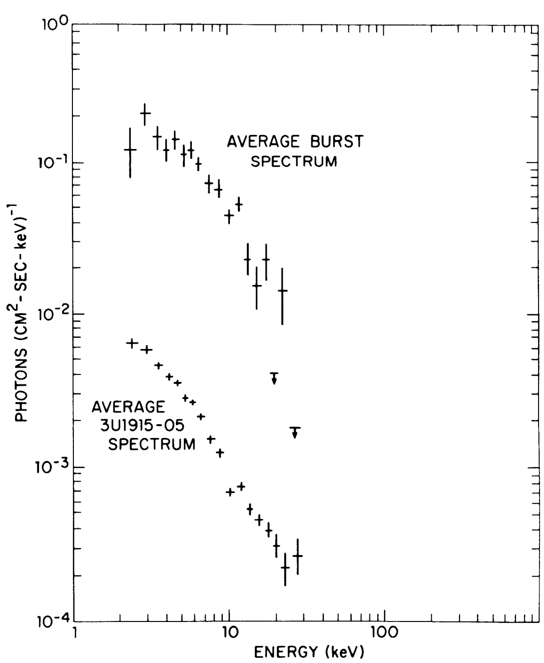

FIG. 1.—The inferred incident spectra for the X-ray source 3U 1915−05 and for the X-ray bursts originating from the vicinity of 3U 1915−05.

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freedom. The thermal bremsstrahlung model requires a $kT > 35$ keV with the best fit value of 50 keV and $N_H = 0.87$ (+1.5, −0.4) $\times 10^{22}$ atoms cm^{-2}, giving a $\chi^2 = 16.0$ for 13 degrees of freedom. In both cases, $y = 6.8 \pm 1.4$. The errors represent the range of values of each parameter within the four-dimensional 90% confidence contour which is found by allowing χ^2 to increase by 7.8 over the best fit. If the absorption edge is due to the 9.3 keV absorption edge of hydrogen-like iron ions, the implied column density of hydrogen-like iron is $1.4 \pm .3 \times 10^{19}$ ions cm^{-2} (cross section from Seaton 1958). If the absorption is due exclusively to the 8.8 keV absorption edge of helium-like iron, the column density would be a factor of 2 less (cross section extrapolated from Brown 1971). An upper limit for the equivalent width of any iron line emission at 6.7 keV is 180 eV at the 90% confidence level.

During the observations of 3U 1915−05, a series of 11 X-ray bursts were detected. The arrival times of the bursts, the interval between bursts, and the centers of the detector field of view during each burst are given in Table 1. All the bursts had similar temporal characteristics, with rise times of ~1 s and decay times of ~5 s, as illustrated in Figure 2. The similarity among the events and the fairly regular occurrence of the events suggest that all the bursts have the same origin. If so, then a 15 deg^2 error box for the location of the burst source can be constructed by taking the intersection of all 11 fields of view.

The statistics for a single burst are inadequate to produce a meaningful spectrum; therefore, we have combined the data from all the bursts to generate an average burst spectrum. Throughout the observations, spectra are accumulated every 41 s. The average burst spectrum was obtained by including for each burst the 41 s accumulation containing the burst peak and the subsequent 41 s accumulation. For background, we used 80 s of data preceding each burst. This result is shown in Figure 1 and has been normalized to the peak burst intensity of $5.2 \pm 1.0 \times 10^{-9}$ ergs cm^{-2} s^{-1} between 2 and 6 keV, approximately 50 times the steady intensity of 3U 1915−05 if we assume that both sources are seen with the same effective area.

Spectral fits to the burst spectrum did not result in

TABLE 1

DATA ON 11 X-RAY BURSTS

Time of Burst (UT) Day (1976)	s	Time Interval to Previous Burst (s)	R.A.(1950)	Decl.(1950)
102	73487	. . .	287.5	−8.54
103	16482	29373	288.6	−7.88
	32860	16421	289.3	−7.36
	68120	35228	289.6	−6.68
	82119	14043	289.7	−6.44
104	26787	31017	290.0	−5.60
	44157	17384	290.3	−4.89
	62013	17323	290.6	−4.54
	82922	21457	290.8	−4.05
105	38770	42203	291.2	−2.85
	59188	20520	290.9	−2.40

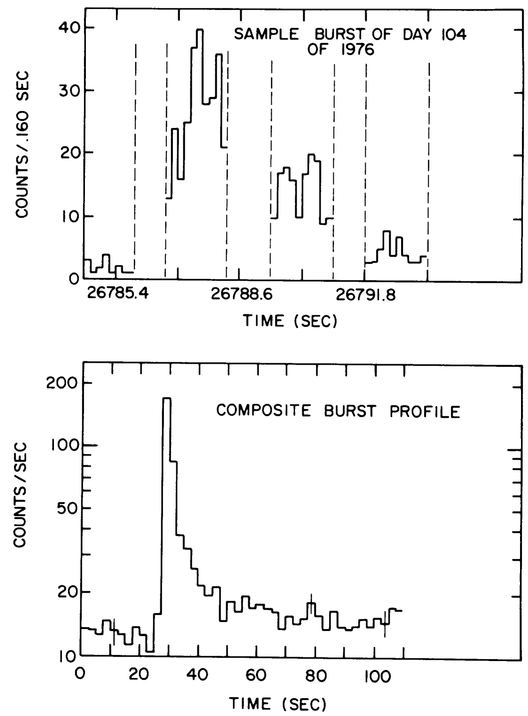

FIG. 2.—*Top*, light curve of one of 11 bursts from the vicinity of 3U 1915−05. The gaps in the data result from the periodic occultation of the detector by the spacecraft. *Bottom*, a composite light curve of the bursts from the vicinity of 3U 1915−05.

acceptable χ^2 values. Since burst spectra have been observed to vary over a burst, it is not surprising that the time-averaged spectrum cannot be well represented by a simple model. The best-fit power law for the average burst spectrum is $\alpha = 1.7$ and $N_H = 8.7 \times 10^{22}$ atoms cm^{-2}. The best-fit thermal bremsstrahlung resulted in $kT = 31$ keV and $N_H = 7.5 \times 10^{22}$ atoms cm^{-2}. The burst spectrum could be fitted equally well by a 2.5 keV blackbody model with $N_H \sim 0$. The addition of an absorption edge at 9.1 keV did not improve the fits. There are not enough X-ray events to generate a separate spectrum for the burst tails, but the hardness ratios indicate that the X-ray emission softens after the burst peak.

III. DISCUSSION

The spectral character of 3U 1915−05 is unique among published X-ray spectra. The source has a hard spectrum modified by an apparent absorption edge at 9.1 keV but with relatively little low-energy absorption. Absorption edges at 7.1 keV have been observed in several X-ray binary sources (for example, Becker *et al.* 1977; Swank *et al.* 1976) and have been attributed to photoelectric absorption due to neutral iron. The presence of these edges is always accompanied by substantial low-energy absorption. The K absorption edge energy for iron depends on the ionization state of the iron. The edge at ~9.1 keV seen in the spectrum of 3U 1915−05 is consistent with the K-absorption edges of either hydrogen or helium-like iron. The high ionization of the absorbing material naturally explains the lack of substantial low-energy absorption, as all the more abundant lighter elements would be fully ionized. Therefore, the spectrum of 3U 1915−05 is consistent with a hard X-ray source ($\geq$35 keV) enveloped in a highly ionized cloud of material. If the abundance of iron in the cloud is near the solar photosphere-coronal average of 3.9×10^{-5} of hydrogen by number (Withbroe 1971), the column density of equivalent hydrogen atoms is $\geq 3.5 \pm 0.8 \times 10^{23}$ cm^{-2} since some iron may be fully ionized.

If the cloud as a whole is in statistical equilibrium, there will be as many recombinations as photoionizations. Some fraction (0.3–0.7) depending on T will recombine to the ground state, resulting in an emission edge which will tend to fill in the absorption edge. Of those which recombine to an excited state, approximately two-thirds will result in a Lα photon at 7 keV. Hence, the depth of the edge gives only a lower limit to the column density of iron; furthermore, there should be two-thirds as many Lα photons as there are photons missing due to the edge. Therefore, if the cloud is spherically symmetric and all the Lα photons escape, we should observe a line of $\sim$300 eV equivalent width, substantially larger than the observed upper limit.

It is easy to construct models to explain the lack of iron emission line. If a spherical cloud was divided by an optically thick, planar disk, the expected iron emission would be halved. In addition, the optical depth at the line center for iron Lα is $\gtrsim 10^3$ times the optical depth in the continuum. This results in long path lengths through the cloud, increasing the probability that the line radiation will be absorbed. A detailed understanding of the lack of an iron line emission feature will require a more complete model of this source.

The high ionization of the absorbing material could result either from collisional ionization in a high-temperature gas or from photoionization by the hard X-rays from the central source. For either case, we can deduce an upper limit on the size of the absorbing cloud which depends on the distance d to the source. It is unlikely that 3U 1915−05, located at $l^{\rm II} = 31^\circ.3$, $b^{\rm II} = -8^\circ.3$, is more distant than 10 kpc.

For a gas in collisional equilibrium, hydrogen- and helium-like iron are the dominant species for temperature T near 10^8 K. If the absorbing cloud is isothermal, has a radius r, and radiates a fraction η of the total observed flux, then

$$r = 2.8 \times 10^{11} \eta \chi^2 (T/10^8 \text{ K})^{-1/2} (d/10 \text{ kpc})^2 \text{ cm}$$

where χ is the fraction of iron in the Fe^{+24} and Fe^{+25} states. Analysis of the spectrum of 3U 1915−05 indicates $\eta < 0.3$ for $T \sim 10^8$ K, resulting in $r < 4 \times 10^{10}$ cm and $n_e > 10^{13}$ cm^{-3}. The cooling time for such a cloud is $\sim 10^2$ s, so there must be a continuous source of heating to maintain the high temperature. The mass required to gravitationally bind the absorbing cloud is $\leq 56\ \eta\chi^2(T/10^8 \text{ K})^{1/2}(d/10 \text{ kpc})^2\ M_\odot$. Therefore, it is possible that the cloud could be bound by a neutron star.

Alternatively, the absorbing material could be photoionized by X-rays from the hard central source. Hatchett, Buff, and McCray (1976) have shown that the ionization state and temperature of a gas in photoionizational equilibrium can be determined from the single parameter $\xi \equiv L_x/nr_x^2$ if the spectrum of the incident X-rays is specified. Here L_x is the luminosity of the X-ray source, n is the local atomic density, and r_x is the distance of the gas from the X-ray source. For a 50 keV incident spectrum, hydrogen-like and helium-like iron will be the dominant species of iron for $\log \xi \simeq 3$. Using $N_{\rm H}$ calculated from the absorption edge as a lower limit to nr_x, we can solve for r_x. If 3U 1915−05 is nearer than 10 kpc, then $L_x \leq 3.4 \times 10^{36}$ ergs s^{-1} between 2 and 20 keV and therefore $r_x \leq 10^{10}$ cm if the cloud is photoionized. In this model, the kT of the electrons at a radius where iron is 50% fully ionized is less than 2 keV for an incident spectrum like that observed for 3U 1915−05, and the cloud could be bound by a 0.5 $M_\odot$ central mass.

Canizares (1976, and private communication to Hoffman *et al.* 1976) has suggested that the time evolution of spectra from the bursters NGC 6624 and MXB 1728−34 can be understood in terms of scattering in a cloud of 10^8 K with $r \sim 10^{10}$ cm and with $n_e \sim 10^{14}$ cm^{-3}. Our data indicate that 3U 1915−05 is surrounded by a highly ionized cloud which could have a similar size and density.

Canizares showed that the diffusion of the X-rays from the burst through the scattering cloud could explain the temporal behavior of the bursts from NGC 6624. The composite burst profile shown in Figure 2 can not be explained this way. The tail of the burst profile in Figure 2 extends to at least 40 s after the start of the burst and drops off in intensity slower than expected from the scattering models. Thus the burst profile cannot result from scattering in a spherical cloud of the sort suggested by Canizares, but instead would seem to require continued X-ray emission from the burster. Recent observations have shown that at least one burst source radiates as a blackbody (Swank *et al.* 1977), and it has been suggested that the burst behavior is consistent with the radiative cooling of a blackbody (Lewin 1977). The burst profile in Figure 2 is consistent with a blackbody cooling curve. Spectra of these bursts with higher time resolution are needed to determine if the evolution of the spectrum of the burst is consistent with a cooling blackbody.

Note added in proof.—Observations by SAS-3 confirmed the identification of 3U 1915-05 as a burst source (Lewin 1977, private communication).

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