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The X-ray spectrum of Cyg X-2

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Summary. The spectrum of Cyg X-2, determined by Ariel V Experiment C observations, is best fitted by a thermal Bremsstrahlung model only at energies higher than ~2 keV. At lower energies an excess of flux above the theoretical curve is clearly present and on occasions there is evidence for a feature between 2 and 3 keV: the latter may be indication of a break in a two-component spectrum or an absorption feature of the type expected from X-ray transfer in an optically thick environment. The 2–10 keV flux of Cyg X-2 is seen to vary by about a factor of 5 between two Ariel V observations 20 months apart. In the present paper we attempt to interpret these observational results in the context of X-ray reprocessing in a neutron star binary system.

Key words: X-ray binaries – Cyg X-2

1. Introduction

Although Cyg X-2 was one of the first cosmic X-ray sources to be optically identified (Giacconi et al., 1967), the nature of this object has remained controversial. While low resolution X-ray spectra in the range 2.5 to 9.0 keV appear to support the hypothesis of a white dwarf binary system very close to the Sun (Branduardi et al., 1980), optical spectroscopic data (Cowley et al., 1979) have been used to construct a model of Cyg X-2 in terms of a neutron star in a long period (~10 d) binary. The results of UV observations seem to favour the latter view (Maraschi et al., 1980). We present here a detailed analysis of the Cyg X-2 spectrum as determined from Ariel V Experiment C observations.

2. Observations

The Ariel V observations were carried out on 28–29 June 1976 and cover a total of 12 satellite orbits, 10 of which are in High Gain (energy range 0.9–9.1 keV) and 2 in Low Gain [1.9–18.7 keV; for a description of the instrumentation see Sanford and Ives (1976)]. One additional orbit was spent observing Cyg X-2 earlier in the satellite lifetime, on the 31 October 1974: the High Gain energy range was then 1.4–13.8 keV.

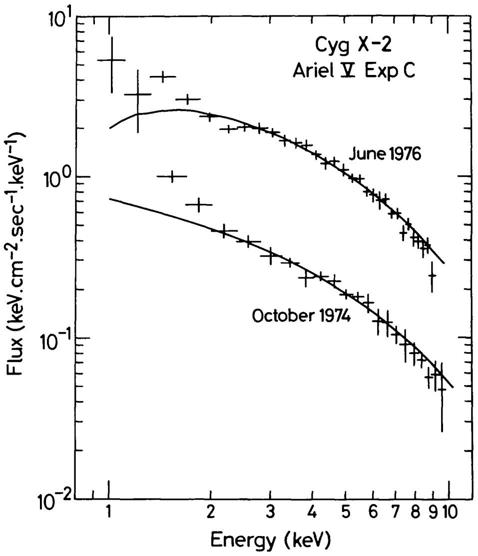

Fig. 1. The 1–10 keV spectrum of Cyg X-2 as seen by Ariel V Experiment C in 1974 and 1976. The solid lines show the thermal Bremsstrahlung (with Gaunt factor) best fits (see Table 1)

2.1. Spectral analysis

The 1–10 keV High Gain spectra of Cyg X-2 from both observations are shown in Fig. 1: out of the June 1976 data only two orbits, the most representative of the behaviour discussed below, were combined and displayed. The solid curves represent the best thermal Bremsstrahlung fits to the data (see Table 1 and text below). It is clear that the data deviate substantially from the fits: on both occasions an excess of counts at low energies is present; in addition, the June 1976 spectrum shows a feature between 2 and 3 keV, which is missing in the October 1974 data. Variability in the strength of the emission below 2 keV and in the depth of the feature is observed from orbit to orbit (~90 min) in the 1976 data.

To exclude that the spectral features in Fig. 1 may be caused by some detector peculiarity we have compared the spectra of Cyg X-2 with those of the Crab Nebula, which is about twice as strong in this energy band and which was observed repeatedly by Experiment C for calibration purposes. No significant deviations from the well

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Table 1. Best fit parameters for the Cyg X-2 Ariel V Experiment C spectra (kT and N_H refer to the thermal Bremsstrahlung component)

Model	Energy Range (keV)	χ^2/dof	kT (keV)	$N_H (\times 10^{22}\ \mathrm{cm}^{-2})$
1976 data				
Thermal Bremsstrahlung	0.9 – 9.1	2.46	4.4 ± 0.2	0.35 ± 0.19
Thermal Bremsstrahlung	1.9 – 9.1	0.75	3.8 ± 0.2	1.32 ± 0.25
Thermal Bremsstrahlung + power law	0.9 – 9.1	0.80	4.0 ± 0.1	fixed (see text)
1974 data				
Thermal Bremsstrahlung	1.4 – 13.8	2.28	4.8 ± 0.1	not fitted
Thermal Bremsstrahlung	2.0 – 13.8	0.82	5.1 ± 0.2	(consistent with 0.0)
Thermal Bremsstrahlung + power law	1.4 – 13.8	0.79	5.2 ± 0.2	fixed (see text)

known power law spectrum are evident in the case of the Crab data (Blissett and Cruise, 1979) and certainly not of the magnitude observed for Cyg X-2.

No strong X-ray source has been reported within ~5° of Cyg X-2 (Forman et al., 1978; Bradt et al., 1979; Warwick et al., 1981; McHardy et al., 1981), so that we would exclude contamination of the flux of Cyg X-2 from being responsible for the features in the spectrum. On the other hand, the bright nature of the source makes contamination from weaker sources, which must have gone undetected so far, negligible.

No significant increase in solar activity, in particular X-ray emission, was recorded at the time of the 1976 observations of Cyg X-2 (Solar-Geophysical Data reports of the US Department of Commerce, 1976–1977). This makes it unlikely that the Cyg X-2 data be contaminated by scattered and fluorescent X-rays from the Earth's atmosphere [a strong flux of atmospheric Argon X-rays at ~3 keV has been observed by Experiment C during large solar flares; Seward et al. (1976)].

We fitted both the 1974 and 1976 spectra of Cyg X-2 in three different ways (the best fit parameters for all cases are given in Table 1): a single thermal Bremsstrahlung is clearly unsatisfactory over the total energy range observed, but produces a good fit when the data below ~2 keV are rejected; the best fit over the complete energy range is obtained when the combination of a thermal Bremsstrahlung and a power law spectrum is used. In this case we maintained the low energy absorption fixed at the value which best fits the data above 2 keV. The turn-over between 2 and 3 keV is responsible for the high column density required to fit the 1976 spectrum; on the other hand, the fit to the 1974 data does not require a significant amount of interstellar absorption because of the presence of the excess of radiation at low energies. The Bremsstrahlung temperatures are very similar in all cases and are consistent with those previously determined by other authors (Bleach et al., 1972; Burginyon et al., 1973; Parsignault and Grindlay, 1978); in fact, a Bremsstrahlung fit to the 1976 Low Gain data (not shown in Fig. 1) produces a best value of temperature in the same range, implying that the thermal model holds at least up to about 20 keV. For both the observations the slope of the power law spectrum which is used to fit the low energy data is extremely steep (photon index larger than 10!) but its determination is affected by very large errors because of the limited energy range over which the fit is performed. There is no evidence of iron line emission at ~7 keV in the Ariel V spectra, in contrast with the positive detections made by ANS (Parsignault and Grindlay, 1978).

Some or all of the feature between 2 and 3 keV may be due to photoelectric absorption by material surrounding the X-ray source: a similar feature, but between 3 and 4 keV, has recently been discovered in the Ariel V spectrum of GX17+2 (Ercan and Cruise (submitted to *Monthly Notices Roy. Astron. Soc.*). The single thermal Bremsstrahlung fit of Table 1 to the 1976 Cyg X-2 data over the total energy range observed is definitely improved by including additional absorption due to *K*-shell photoionization of Mg and Si hydrogen- and helium-like ions: the χ^2 value decreases from 71.3 for 29 degrees of freedom ($<0.1\%$ probability of exceeding such value if the deviations from the fit are due to random fluctuations) to 41.6 for 29 degrees of freedom (6% probability of observing a larger value of χ^2). A problem with this interpretation is the lack of any absorption feature at energies higher than ~2 keV: at the plasma temperatures likely to be present around the X-ray source, elements with lower atomic number than Mg and Si would be almost fully ionized and would not contribute substantial absorption at energies below that of the observed feature, but absorption by S and Fe ions is expected to be significant at energies above it, as well as Fe emission around 7 keV (Ross, 1979). To avoid this, sulphur and iron should be very underabundant in the plasma with respect to cosmic values, unless emission lines are filling in the absorption, the details of the spectrum being lost in the convolution with the energy resolution of the detector. Moreover, the inclusion of a Fe line, even weak, would only worsen the fit.

On the other hand, the absorption could be due to the unresolved combined contributions of photoionization of neutral or near-neutral Mg, Si and S atoms. Taking the intensity at the bottom of the edge to be 60% of that at the edge top and an average cross section at the edge energy of $1.5\ 10^{-19}\ \mathrm{cm}^2$ (Daltabuit and Cox, 1972), an equivalent hydrogen column density of $\sim 10^{23}\ \mathrm{cm}^{-2}$ is obtained: this is well over an order of magnitude higher than the column determined from the low energy absorption in the continuum spectrum. A similar discrepancy has already been noticed in the case of the absorption features observed in the spectrum of 4U0900-40 (Vela X-1; Kallman and White, 1982): possible explanations advanced in that case, which could apply here to Cyg X-2, are partial ionization of the gas around the X-ray source (the column of neutral hydrogen would then not be very indicative of the amount of material actually present), altered elemental abundances with respect to cosmic values or different levels of ionization for low and high *Z* elements.

2.2. *Source intensity*

The 2–10 keV intensities of Cyg X-2 during the 1974 and 1976 observations are $2.3\ 10^{-9}$ and $1.2\ 10^{-8}\ \mathrm{erg\ cm^{-2}\ s^{-1}}$, respectively, which correspond to an X-ray luminosity of 1.7 and 8.7 10^{37} erg s^{-1} for a distance of 8 kpc to the source. The range of variability between the two observations is somewhat larger than that seen by other satellites (Bradt et al., 1979; Holt et al., 1979), the maximum Ariel V intensity being consistent with the highest values reported in the literature (Forman et al., 1978; Bradt et al., 1979; Parsignault and Grindlay, 1978). The strength of the emission observed in the soft X-ray band (below 2 keV) during the 1976 Ariel V observation is 6.5 10^{-9} erg cm^{-2} s^{-1}, which makes the ratio of hard (2–10 keV) to soft X-ray luminosity about 2 to 1 on that occasion.

3. Discussion

The presence of an excess of radiation at low energies in the Ariel V spectrum of Cyg X-2 is not surprising: Ariel VI observations (Cruise et al., 1981) show that Cyg X-2 has a significant, variable emission between 0.1 and 0.3 keV [although this can hardly be reconciled with the cut-off expected for the maximum H I column density of 2.1 10^{21} cm^{-2} in the direction of Cyg X-2 reported in the 21 cm survey of Heiles (1975)]. Earlier rocket data (Bleeker et al., 1972) also suggest that two separate processes may be responsible for the low and high energy X-ray emissions of Cyg X-2. On the other hand, recent work by Pravdo (1983) shows that the spectrum of the source, accumulated over 123 s during a 5-d interval in December 1977, is well approximated down to ~0.5 keV by a single thermal Bremsstrahlung model with absorption by interstellar material (~2.7 10^{21} cm^{-2}).

If the feature detected by Ariel V in the spectrum of Cyg X-2 is, even only in part, due to absorption, a strong flux of soft X-rays is required to partially ionize the gas around the X-ray source: the intense low energy emission observed by Ariel V and Ariel VI shows that such soft flux does exist, even if not persistently. Depending on the temperature and the strength of this flux, the ionization structure of the plasma around Cyg X-2 is likely to change, as well as the strength of the absorption features at higher energy. From this point of view it is interesting that in the Ariel V spectra absorption may be present when the overall intensity of the source is higher (see Fig. 1), which would give support to the idea that the strength of the soft X-ray flux is related to the formation of the absorption features.

Several models can explain the low energy excess in the spectrum of Cyg X-2 qualitatively, in particular the opaque shell model of Her X-1 by McCray and Lamb (1976). Other possibilities may exist for soft X-ray emission from low temperature regions of accretion disks surrounding neutron stars. In both cases the soft X-rays are emitted from outer regions of the system, where absorption features may also be formed. We can try to quantify this effect in the context of the Compton-thick shell model of Ross (1979): the ionization of the gas surrounding the central source of X-rays is then determined by the ratio of the energy density of the radiation field to the gas density. This is approximately proportional to the parameter

$$\xi' = L_0 \tau_T / n_H R^2 ,$$

where L_0 is the central X-ray luminosity, n_H the gas density, R the inner radius of the shell and τ_T, the shell Thomson thickness, can be written as $\tau_T = 1.2 n_H \sigma_T \Delta R$, with σ_T being the Thomson cross-section and ΔR the shell thickness (Ross, 1979). Taking $\Delta R = R/100$ (a thin shell) and substituting:

$$\xi' = 8\ 10^{-27} L_0 / R .$$

The occasional presence of absorption features in the X-ray spectrum can then be directly related to the variability of the central X-ray flux. Thus we require $\xi' \lesssim 10^3$, and then $L_0 \lesssim 0.13\ 10^{30} R$ erg s^{-1}, to maintain the gas highly, but not fully, ionized (see the discussion in Ross, 1979), such that K-shell photoionization can still occur on intermediate Z elements. At much lower values of L_0 (e.g. the 5-fold decrease in intensity between the two Ariel V observations of Cyg X-2) the gas may not be sufficiently ionized for substantial K-shell photoionization to occur.

4. Conclusions

For a complete consistency of all the observational data of Cyg X-2, X-ray as well as optical, it is still to be assessed theoretically whether neutron star binaries can display the same X-ray spectral behaviour expected so far only for white dwarf systems. In practice, a number of X-ray bursters, generally believed to be neutron star binaries, have shown the luminosity-spectral hardness correlation (Parsignault and Grindlay, 1978; Mason et al., 1976; White et al., 1978, 1980) originally taken as indication of the degenerate dwarf nature of Cyg X-2 (Branduardi et al., 1980). This type of behaviour is now suspected to be an intrinsic property also of the neutron star X-ray emission and not exclusively the signature of an accreting degenerate dwarf (see also the discussion of Cyg X-2 by Kylafis and Lamb, 1982). On the other hand, the intense and variable low-energy emission in the spectrum of Cyg X-2 is suggestive of a reprocessing shell model on the lines of that proposed by McCray and Lamb (1976) for Her X-1. The compact object in that case is unequivocally a neutron star. Such observational evidences lead us to conclude that the white dwarf versus neutron star nature of Cyg X-2 is no longer a critical issue as was believed at first.

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References

Bleach, R.D., Boldt, E.A., Holt, S.S., Schwartz, D.A., Serlemitsos, P.J.: 1972, *Astrophys. J.* **171**, 51

Bleeker, J.A.M., Deerenberg, A.J.M., Yamashita, K., Hayakawa, S., Tanaka, Y.: 1972, *Astrophys. J.* **178**, 377

Blissett, R.J., Cruise, A.M.: *Monthly Notices Roy. Astron. Soc.* **186**, 45

Bradt, H.V., Doxsey, R.E., Jernigan, J.G.: 1979, *Advances Space Exploration* **3**, 3, Pergamon Press, Oxford

Branduardi, G., Kylafis, N.D., Lamb, D.Q., Mason, K.O.: *Astrophys. J.* **235**, L153

Burginyon, G., Hill, R., Palmieri, T., Scudder, J., Seward, F., Stoering, J., Toor, A.: 1973, *Astrophys. J.* **179**, 615

Cowley, A.P., Crampton, D., Hutchings, J.B.: 1979, *Astrophys. J.* **231**, 539

Cruise, A.M., Goodall, C.V., Bedford, D.K., Campbell, D.J., Carpenter, G.F., Cole, R.E., Culhane, J.L., Osborne, J., Pollock, A.M.T., Willmore, A.P., Zarnecki, J.: 1981, *Adv. Space Research* **1**, 211

Daltabuit, E., Cox, D.P.: 1972, *Astrophys. J.* **177**, 855

Forman, W., Jones, C., Cominsky, L., Julien, P., Murray, S., Peters, G., Tananbaum, H., Giacconi, R.: 1978 *Astrophys. J. Suppl.* **38**, 357

Giacconi, R., Gorenstein, P., Gursky, H., Usher, P.D., Waters, J.R., Sandage, A., Osmer, P., Peach, J.: 1967, *Astrophys. J.* **148**, L129

Heiles, C.: 1975, *Astron. Astrophys. Suppl.* **20**, 37

Holt, S.S., Kaluzienski, L.J., Boldt, E.A., Serlemitsos, P.J.: 1979, *Astrophys. J.* **233**, 344

Kallman, T.R., White, N.E.: 1982, *Astrophys. J. Lett.* **261**, L35

Kylafis, N.D., Lamb, D.Q.: 1982, *Astrophys. J. Suppl.* **48**, 239

Maraschi, L., Tanzi, E.G., Treves, A.: 1980, *Astrophys. J.* **241**, L23

Mason, K.O., Charles, P.A., White, N.E., Culhane, J.L., Sanford, P.W., Strong, K.T.: 1976, *Monthly Notices Roy. Astron. Soc.* **177**, 513

McCray, R., Lamb, F.K.: 1976, *Astrophys. J.* **204**, L115

McHardy, I.M., Lawrence, A., Pye, J.P., Pounds, K.A.: 1981, *Monthly Notices Roy. Astron. Soc.* **197**, 893

Parsignault, D.R., Grindlay, J.E.: 1978, *Astrophys. J.* **225**, 970

Pravdo, S.H.: 1983, *Astrophys. J.* **270**, 239

Ross, R.R.: 1979, *Astrophys. J.* **233**, 334

Sanford, P.W., Ives, J.C.: 1976, *Proc. Roy. Soc. London* A **350**, 491

Seward, F.D., Horton, B., Pollard, G., Sanford, P.W.: 1976, *Nature* **264**, 421

Warwick, R.S., Marshall, N., Fraser, G.W., Watson, M.G., Lawrence, A., Page, C.G., Pounds, K.A., Ricketts, M.J., Sims, M.R., Smith, A.: 1981, *Monthly Notices Roy. Astron. Soc.* **197**, 865

White, N.E., Charles, P.A., Thorstensen, J.R.: 1980, *Monthly Notices Roy. Astron. Soc.* **193**, 731

White, N.E., Mason, K.O., Sanford, P.W., Johnson, H.M., Catura, R.C.: 1978, *Astrophys. J.* **220**, 600