OBJECTIVE GRATING SOFT X-RAY SPECTROSCOPY OF COMPACT BINARY X-RAY SOURCES

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INTRODUCTION

The presence of objective transmission gratings on the two recent X-ray telescope experiments, the Einstein and EXOSAT Observatories, has opened up a new avenue of research in X-ray astronomy by enabling us, for the first time, to obtain moderate-to-high resolution spectra of cosmic sources in the soft X-ray band ($\lambda \sim 5$-200 Å). Both experiments incorporated gold bar transmission gratings with line densities of 500 l/mm and 1000 l/mm which could be inserted into the X-ray optical path at the exit from a grazing incidence mirror. At short wavelengths, the resolution was determined principally by the spatial resolution of the detector-telescope combination. For Einstein, this was $\Delta\lambda \sim 0.4$ Å for the 1000 l/mm grating and ~ 0.8 Å for the 500 l/mm grating. For EXOSAT, the resolution was somewhat worse: $\Delta\lambda \sim 1.5$ Å for the 1000 l/mm grating, and ~ 3 Å for the 500 l/mm grating. (More complete descriptions of these instruments can be found in Seward et al. 1982 and de Korte et al. 1981.)

The peak effective area of the objective grating experiments was ~ 1 cm^2 in both cases. This is rather low by cosmic X-ray astronomy standards, and the spectroscopic observations performed thus gave useful results only for relatively bright sources. Compact X-ray binaries, which are among the brightest soft X-ray sources in the sky, were consequently the most common objects observed. These are believed to be interacting binary systems containing a relatively normal star which transfers matter onto a collapsed companion, either a neutron star, a black hole, or a white dwarf. The energy released by gravitational infall heats the accreting material to temperatures $\sim 10^8$ K thereby producing copious X-ray emission. Moderate-to-high resolution soft X-ray spectroscopy of such sources can be useful primarily as a probe of this circumsource accreting flow. The transfer of the intense X-radiation outward through the cooler, less dense, accreting gas can produce a number of observable spectral features in the soft X-ray band. K-shell lines and edges of partially ionized CNO and L-shell lines of partially ionized Fe are particularly important. Measurements of such features can yield sensitive constraints on the density, temperature, and geometry of the surrounding medium.

Here we present a brief review of some of the spectra of bright X-ray binaries that have been obtained with the objective grating instruments on Einstein and EXOSAT. The data are quite complex, and at this point, only general, qualitative conclusions can be drawn. However, the data do suggest the power of soft X-ray spectroscopic observations for this field, and provide an important impetus for the development of higher sensitivity, higher resolution grating experiments on future satellite facilities.

SCORPIUS X-1

We begin with the Einstein observations of Sco X-1. Four separate exposures were taken, each $\sim$ 5000 s long. The raw count spectra resulting from these observations are shown in Figure 1 below. As can be seen, the data do exhibit some obvious discrete spectral structure. In order to interpret such features however, it is useful to first model

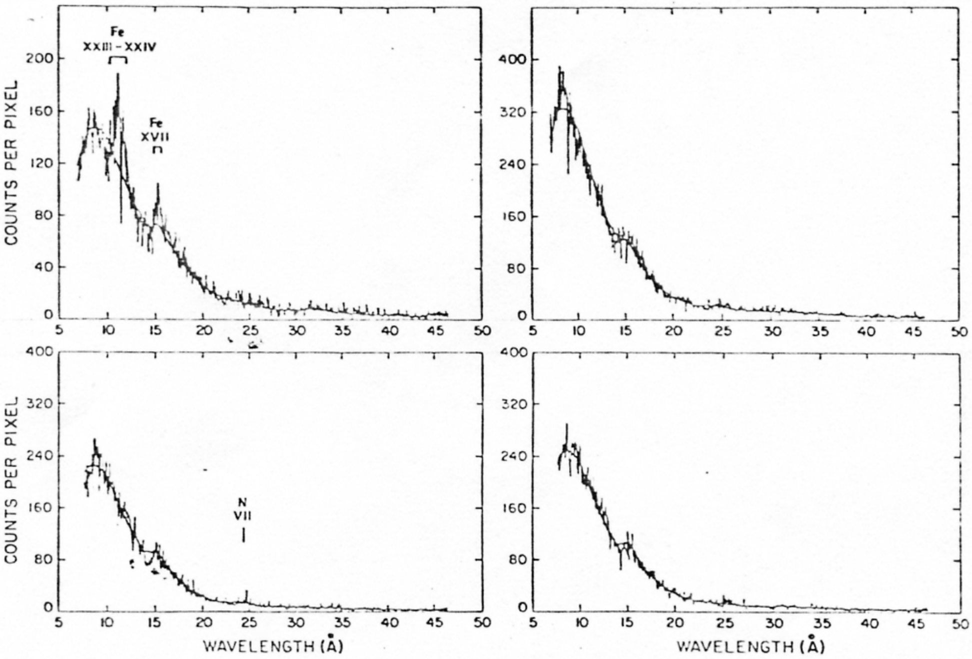

Figure 1. Raw Einstein objective grating spectra of Scorpius X-1. Obvious emission features are marked. The solid lines represent the best fit model continuum spectra.

the continuum; otherwise it is difficult to discriminate regions of true continuum from weak emission or absorption complexes. The model we have chosen to fit involves a slightly Compton-deformed bremsstrahlung continuum absorbed at long wavelengths by intervening material. Such a model has always been found to provide an acceptable fit to the low resolution spectra which have been obtained in the past.

When we perform these model fits, we find the first interesting fact about these spectra: even after allowing for the presence of discrete features, it is impossible to obtain near acceptable χ^2's without also allowing for abundance anomalies in the absorbing medium, an underabundance of oxygen and an overabundance of nitrogen with respect to cosmic values. Such anomalous abundances are suggestive of CNO processing associated with hydrogen burning. This result is of interest for Sco X-1 since the secondary star in that system is thought to be evolved (Cowley and Crampton 1975). It is possible that processed material produced in the hydrogen burning layers of the evolved secondary could be dredged to the surface via convection, and then transferred to the compact object through the accreting flow. The abundance anomaly thus strongly suggests that the absorbing component in the spectra is associated with accreting material, which is local to the system.

The best fit continuum models (incorporating these anomalous abundances) are plotted as solid continuous lines in Figure 1. Discrete residuals to the fits, which are suggestive of emission features, are marked and line identifications are indicated where possible. Typical equivalent widths for these features are ~ 0.1 Å. The range of ions observed is striking; it is indicative of a large spread in temperature, $\sim 10^5$–10^8 K. The N VII line visible in the third spectrum is particularly interesting. Note that it is not accompanied by O VII lines near 22 Å or an O VIII line near 19 Å. In most X-ray transfer situations where the N VII line is expected to be prominent, the oxygen lines would be at least of comparable intensity for a normal abundance medium. Thus, our observations suggest that the N/O ratio is high in the line emitting component as well. For a more complete discussion of these spectra, see Kahn, Seward, and Chlebowski (1984).

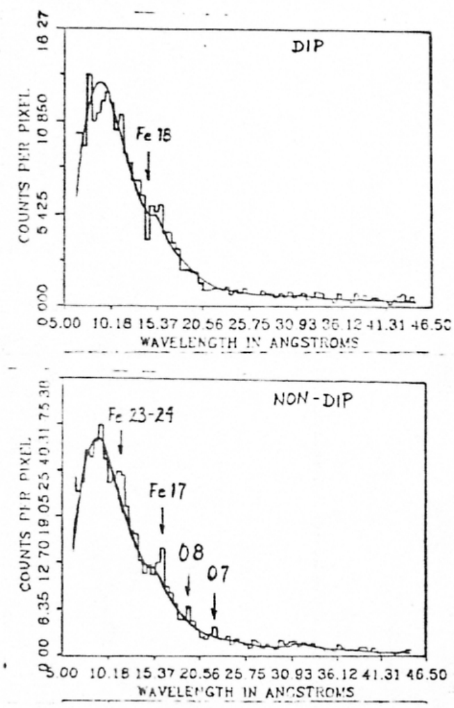

Figure 2. Einstein objective grating spectra of Cygnus X-2 acquired during "dip" and "non-dip" intervals. The smooth solid lines are model continua.

CYGNUS X-2

The Einstein grating study of Cyg X-2 is interesting because the source was quite variable during the course of the observation. In particular, the zero order countrate exhibited a series of recurrent dips involving reductions in flux by as much as 40%. The dip durations were ~ 1000 s and they were separated by time scales of order several thousand seconds. The Monitor Proportional Counter (MPC) on Einstein, which observed the source simultaneously at higher energies (2-20 keV), also detected these dips, however the fractional reduction in flux was not as large for that instrument. Hence, the overall continuum spectrum of the source must have "hardened" during the dips.

In order to investigate the matter further, we compiled grating spectra of the source separately for the "dip" and "non-dip" intervals. The results are shown in Figure 2. Best fit model continua have been derived in the same manner as for Sco X-1. For Cyg X-2, we also require an underabundance of oxygen and an overabundance of nitrogen in the absorbing medium. That is, perhaps, not surprising since the companion star for Cyg X-2 is known to be evolved as well (Cowley, Crampton, and Hutchings 1979). Note that the spectra during "dip" and "non-dip" states are different.

The "non-dip" spectrum exhibits emission lines, most of which can be readily identified. These do not appear in the "dip" spectrum. Instead there is an apparent absorption line probably associated with Fe XVIII. The derived absorbing column density is also higher in the "dip" spectrum as expected form the spectral hardness variations.

This spectral behavior suggests an interpretation of the dips. If we imagine an obscuring blob passing in front of our line of sight, we expect an increase in the photoelectric absorption and may see absorption lines like Fe XVIII. As the blob moves away, the column density should decrease and the flux should increase. In addition, the irradiated face of the blob should become visible, and we might expect to see emission lines due to recombination by atoms which have been ionized by the incident X-ray flux. We are presently working to quantify this scenario and derive concrete constraints on the density of this blob and its location with respect to the central source (Vrtilek et al. 1984).

4U1543-47

4U1543-47 is an X-ray transient previously observed by experiments on several X-ray satellites. It was detected again in outburst by the Tenma Observatory in late August of 1983, and the EXOSAT Observatory team was quickly notified so as to facilitate an EXOSAT pointing while the source was still bright. The EXOSAT observation lasted ∿ 6000 s. Both the 500 1/mm and the 1000 1/mm gratings were used simultaneously together with higher energy experiments.

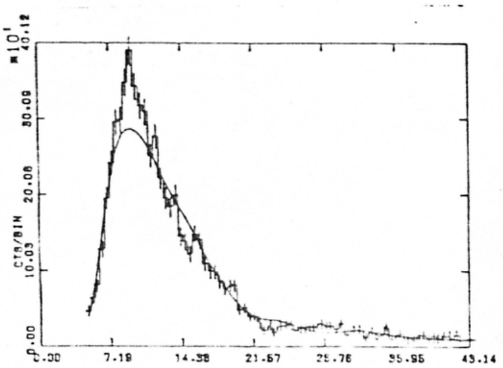

Figure 3. EXOSAT objective grating spectra of 4U1543-47 during outburst. The solid line is the best fit model continuum. Note the excess near 10 Å in the data.

The raw 1000 1/mm spectrum obtained during the first half of the observation is shown in Figure 4 along with the best fit model continuum. Interestingly enough, the model fits for this source also require a marked underabundance of oxygen. Even after allowing for abundance anomalies however, the fit is still poor, primarily because of a large excess at short wavelengths, $\lambda \sim$ 8-11 Å. This is observed on both sides of the spectrum and with both gratings. If we explicitly add an emission line to the model, we can obtain a reasonable fit to the data, with a required line equivalent width ∿ 0.6 Å. However, the best fit wavelength, $\lambda \sim 9.8$ Å, does not correspond to any known transition expected to be prominent. The line is also unresolved; an upper limit to the intrinsic width is ∿ 0.2 Å. It is interesting to note though that the best fit continuum model parameters agree well with those derived from the higher energy data. These results are preliminary, but they do suggest that future grating observations of X-ray binaries may yield surprises.

References

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