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The Stellar Coronal X-ray Explorer: STCOEX

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A. Introduction.

With the end of the observational phase of the *Einstein Observatory* mission, it behooves us to consider the status of the newly-born field of stellar x-ray astronomy. Although *Einstein* clearly allowed a quantum leap over previous observations of x-ray emission from stars (Vaiana *et al.* 1981), its relatively short lifespan allowed only a fraction of the variety of projects, developed in response to this instrument's capabilities, to be completed. In response to the consequent perceived need for further observational capability, we have conducted a overview of the available *Einstein* data for the purpose of deciding which projects will *both* in all probability not be completed by future analysis of the *Einstein* data *and*, in addition, seem to us to be of particular importance for the study of stellar surface "activity"; a natural outgrowth of this analysis was the development of design criteria for a follow-up mission to *Einstein*, one whose primary emphasis would be on stellar observations, and whose general capabilities lay within the scope of the NASA Explorer program. In the following, I will attempt to briefly review the criteria which lead us to the desired instrumental capabilities (§ B); and provide an overview of the proposed instrument and some of its capabilities, as indicated by our simulations (§ C).

B. Scientific Goals and Design Criteria.

One of the remarkable aspects of the stellar observations made possible by the *Einstein Observatory* was their serendipity: the instrumentation and the observing plans were not optimized for stellar observation, but rather for primarily extragalactic studies. In spite of this lack of optimization, well in excess of a third of all guest observer programs focussed on stars; and the stellar survey constituted one of the major research areas of the Consortium groups. What are some of the principal scientific problems, and to what extent have they been resolved? In the following, I will briefly recap some of the major issues, and attempt to define the work which remains to be done.

1. Dependence of Coronal Plasma Parameters on the Characteristics of the "Underlying" Star. The *Einstein* observations have enabled us to sketch in broad outline the x-ray emission properties of stars throughout the H-R diagram; however, in many portions of the H-R diagram, the data is relatively sparse (because of severe restrictions on the allowable observing times). In particular, it has not been possible to assemble uniform, unbiased (viz. volume-limited) samples for every spectral types and luminosity classes. In consequence, phenomenological studies of the variation of x-ray luminosity with stellar parameters such as rotation and mass loss rate may remain biased by selection criteria for several stellar categories because (at least in the beginning of the mission) emphasis was largely placed on targets most likely to be x-ray sources. More severe difficulties beset the plasma diagnostics (such as temperature analysis). the strong constraints on observing time allowed only a very limited sample of stars to be examined by the higher-resolution spectrometers on *Einstein*, such as the OGS and the SSS. Thus, questions regarding possible changes in spectral characteristics along the 'dividing line' separating low and high mass loss late-type evolved stars (cf. Ayres *et al.* 1981); soft x-ray absorption and possible multiple temperature component structure in OB stars; and flare spectroscopy, may all be only partially resolved. Furthermore, the quite limited sensitivity of relatively high resolution spectroscopy ($\lambda/\Delta\lambda$ > 100) on *Einstein* prevented any study of line broadening or doppler shift effects; the latter is particularly of interest in the case of OB stars, since some models predict rapid outflow of the hot plasma (which may be observable with $\lambda/\Delta\lambda \sim 300$-$1000$). The observational requirements thus call for pointings with point source sensitivities of several times 10^{-15} erg/sec/cm^2, in conjunction with spectroscopic instruments capable of resolution in excess of 100, and with line sensitivities of order 10^{-14} erg/sec/cm^2.

2. *Temporal Variability.* Again because of observing time constraints, virtually all temporal variability data for *Einstein* stellar targets are restricted to the few thousand seconds of contiguous observing time; in only a few select cases (for example, for some flare stars and OB associations) are data spanning substantially longer intervals available – and virtually without exception, the longer data base showed evidence for substantial variability. It is evident that 'coronal' emission from stars is highly variable on a wide range of time scales, from seconds or less (flares), to days and weeks (viz. rotational modulation), to months and possibly longer time scales (cycles?). Such variability in stellar 'activity' is seen by ground-based observers (e.g., in Ca II), but only in a very restricted portion of the H-R diagram: in contrast, x-rays allow us to look for activity modulation (via rotation and/or cycles) in stars independent of spectral type or luminosity class, including stars in the spectral range O - A. These observations therefore call for the ability to carry out extended observations (> 10^5 sec) which can be repeated on time scales ranging from 10^6 sec to 10^8 sec.

3. *Galactic Effects of Stellar Activity.* In addition to being a major research area in its own right, stellar x-ray astronomy forms a new bridge between the stellar astronomers and the galactic and extragalactic astronomers: the radiative and particulate emission of active stars may well contribute significantly to the radiation field and matter content of the galaxy. For example, Rosner *et al.* (1981) have shown that late-type dwarf stars contribute a not insignificant amount of radiation to the galactic component of the diffuse soft x-ray background between ~ 0.28-1.0 keV. Because of *Einstein*'s spectral coverage, the stellar contribution at lower energies is not well established (as it depends sensitively on the assumed 'coronal' temperature). Furthermore, the limited effective spectral resolution did not permit relative elemental abundance analysis; such analysis is of great interest for studies of the elemental composition of stellar mass input to the ISM (as it is known from solar observations that the photospheric and coronal/wind abundances are not identical). The necessary observational capability to conduct such studies corresponds to that of § B.1 above.

4. *Desired Instrument Characteristics.* In order to place the instrument discussion on concrete grounds, we shall adopt the following desirata.

(i) *Energy Range:* ~ 10-200 A; this range encompasses virtually all of the significant spectral lines of interest to coronal observations.

(ii) *Optics:* Imaging, with spatial resolution better than ~ 1'; such resolution is required both for accurate target identification and for optimal signal-to-noise.

(iii) *Detectors:* Photon-counting (i.e., IPC or HRI-like); this requirement follows from the necessity of observing flares on sub-second time scales (so that, for example, read-out noise of integrating detectors becomes a significant liability). Note, however, that CCD detectors may be preferable for extremely-high sensitivity observations for which high temporal resolution is not required.

(iv) *Spectroscopy:* High throughput, with resolution in excess of 100 (300 for OB star wind diagnostics), calls for transmission or reflection gratings.

(v) *Sensitivity:* Assuming that of order 1000 pointings (with spectroscopy) are to be carried out on a time scale of 2 years, with sufficient sensitivity to probe stars down to a level of 10^{27} erg/sec at distances of order 50 pc (these numbers will yield a sufficiently large sample to carry out statistical analysis of luminosity functions throughout the H-R diagram), one requires a point source sensitivity @ 10^5 sec approximately 3-4 times that of *Einstein*.

C. **Instrument Characteristics.**

Following the above considerations, we have recently developed two versions of a trial payload (the STellar COronal EXplorer) which meets in essentially all respects the observational desirata. Perhaps the most crucial aspect of the design is that the instrument is *dedicated* to stellar observations. This point is not to be slighted: the character of stellar observing programs (i.e., large numbers of very extended pointings, with substantial degree of repetition) is such that it severely conflicts with the requirements of, for example, extragalactic observations; in this circumstance, combined missions may well be false economy as the principal scientific goals (which presumably underly such ventures) may not be realized. This emphasis on *dedication*, however, does not exclude the possibility of including non-stellar programs whose observing strategies do not overtly conflict with stellar observations (such as observations of galactic high-luminosity x-ray sources).

Figure 1 shows a schematic of the 'simpler' instrument; the optics consist of a nested pair of classical paraboloid-hyperboloid mirror assemblies, together with a movable objective transmission grating and an HRI and imaging proportional counter (PSPC) in the focal plane (mounted on a stage so that the entire dispersed spectrum may be explored); the more 'complex' design simply calls for two additional nested mirror assemblies, which results in a rough doubling of the instrument effective area. The physical characteristics of the instruments and the relevant sensitivities in both the imaging and spectroscopic modes are given in Tables 1 and 2; and graphs of the total effective area of the instrument in the high resolution mode and of the resolving power are shown in Figures 2 and 3. It is to be noted that these results are not speculations, but rather reflect the current state-of-the-art in detector and transmission grating technology: no development is required to obtain such capabilities.

In order to appreciate the power of such an instrument, we show first the range of spectral lines (and source temperatures) accessible to observation (Table 3): the STCOEX can observe coronal line emission from plasma in the temperature range $5.6 < \log T < 7.5$; the lines chosen take advantage of the spectral sensitivity of the instrument, and so are not just marginally detectable. A more revealing analysis is to fully simulate a typical observation. Consider an observation of an RS CVn star at ~50 pc, whose volume emission measure is $\sim 10^{53.4}$ cm^{-3}; the source spectrum is shown in Figure 4 (using recent Raymond 1980 calculations with solar abundances). We have simulated a STCOEX observation by folding this source spectrum through the instrument response (unless otherwise stated, for the 2-mirror system), including the mirror reflectivities, the grating transmission, the detector sensitivities, and the instrument resolution (including mirror pfr and abberations for a coma-corrected grating). If detector noise is *not* taken into account (but photon statistics are), one obtains the spectrum shown in Figure 5 in 10^4 sec; adding detector noise (we assume a background of 1 ct/sec over the entire HRI) then leads to the spectrum shown in Figure 6. Comparing Figs. 4 and 6, we see that a 10^4 sec exposure is sufficient to allow one to resolve most of the strong lines in the source spectrum; however, the limited count statistics would not permit sensible line ratios to be calculated. If one goes to longer exposure times, this restriction is completely eliminated: Figure 7 shows what can be accomplished in 10^5 sec, using the 4-mirror system; again, both photon statistics and detector noise have been taken into account in the simulation. Spectroscopy of such resolution and sensitivity, in combination with the capability for dedicated observations, will clearly allow the observational goals outlined above to be met.

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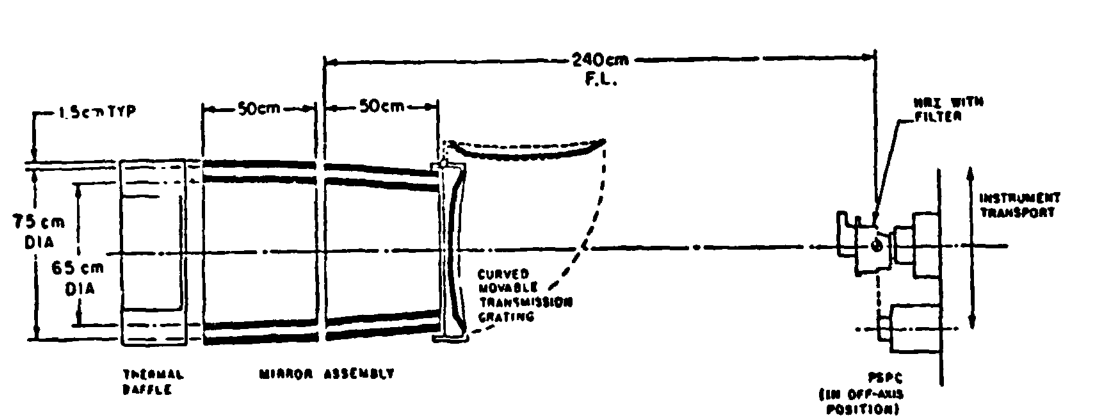

Figure 1: Schematic of the STCOEX, showing the principal instrumentation. Only the 2-mirror system is shown; an alternative design calls for 2 additional concentric mirror assemblies.

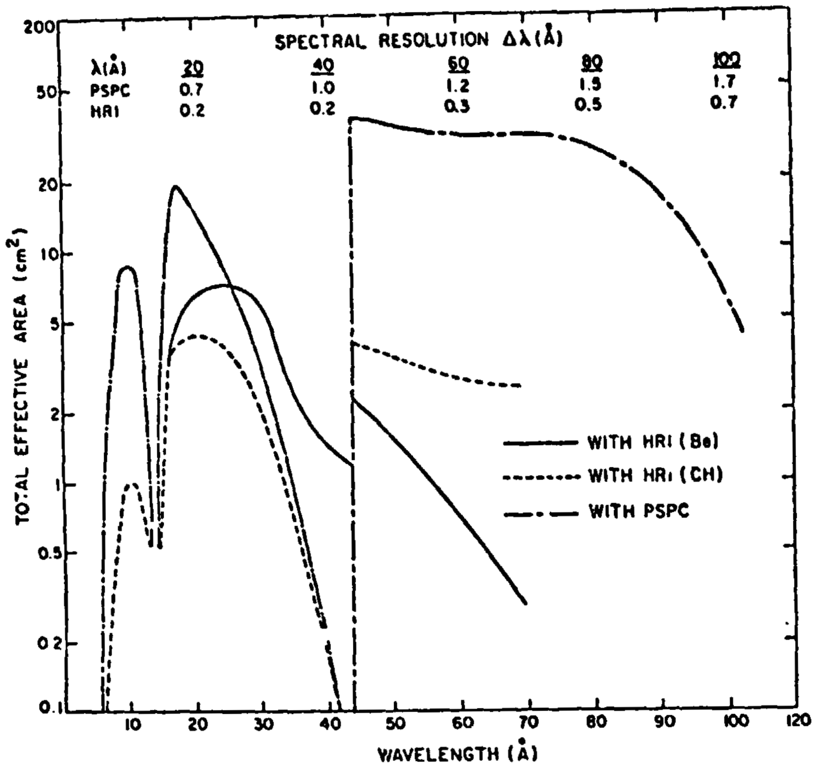

Figure 2: Total effective area of the 2-mirror STCOEX design, including mirror reflectivities, transmission grating performance, and detector sensitivity. We show results for the HRI with either a Beryllium (solid) or organic (dashed) filter, and for the imaging proportional counter (PSPC; solid/dashed). Note that the grating spectral resolution with the high-sensitivity PSPC would be comparable to or somewhat better than that of the *Einstein* SSS.

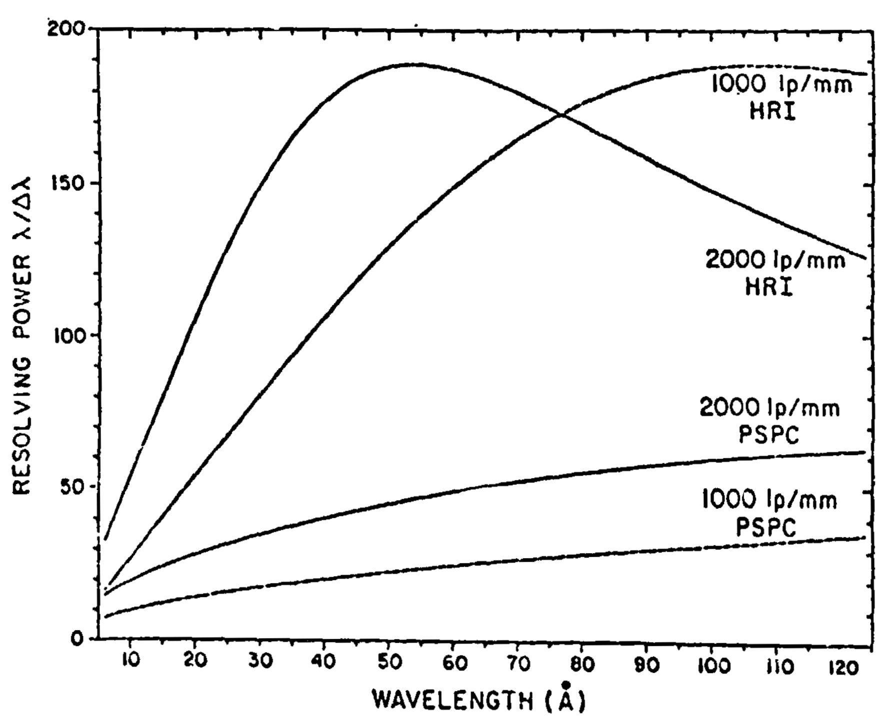

Figure 3: Detailed spectral resolution of the transmission grating for two different grating periods and the two possible focal plane detectors.

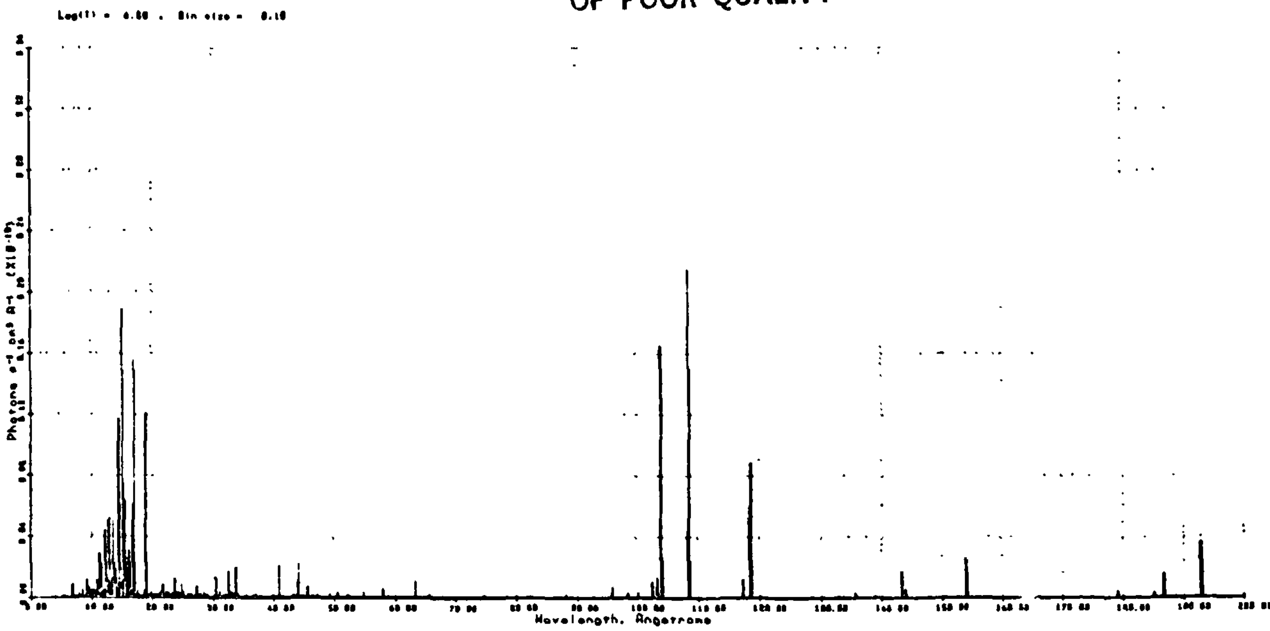

Figure 4: Source spectrum for an 'active' late-type star, with T = $10^{6.8}$ K; the model is that of Raymond (1980).

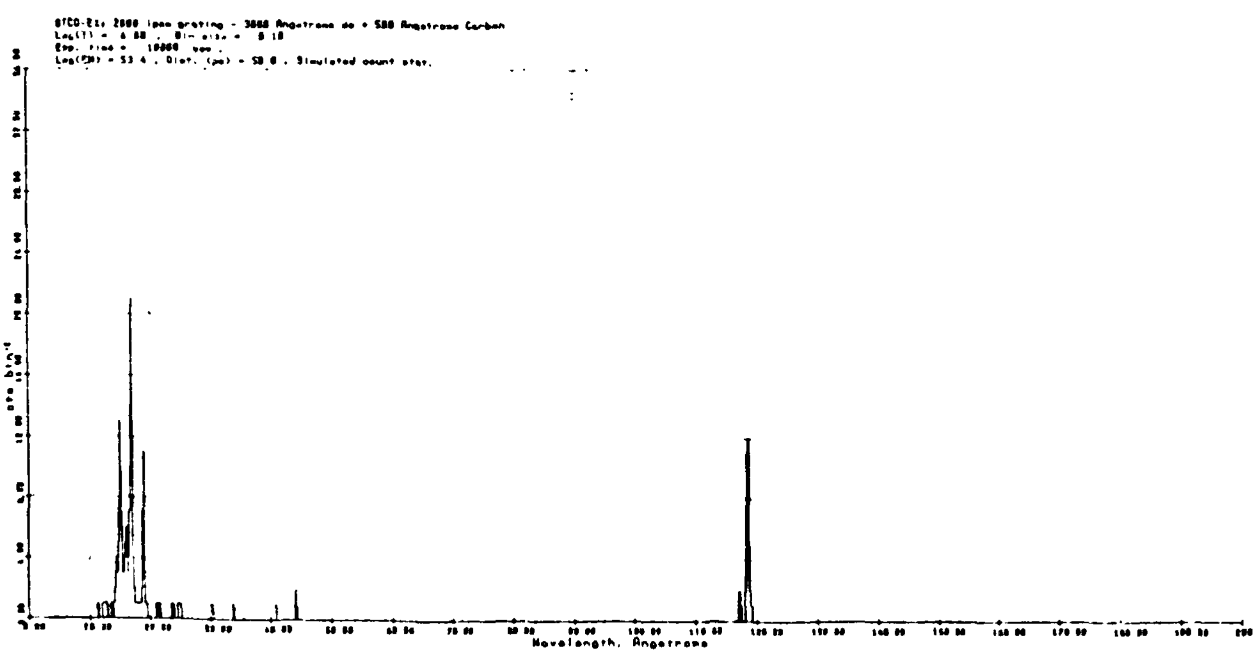

Figure 5: Convolution of the source spectrum of Fig. 4 with the total instrumental response of the 2-mirror design, assuming a source volume emission measure of $10^{53.4}$ cm^{-3} at a distance of 50 pc; we assumed the Beryllium filter, use of the 2000 lpmm grating, an exposure time of 10^4 sec, and *no detector noise* (photon statistics were taken into account).

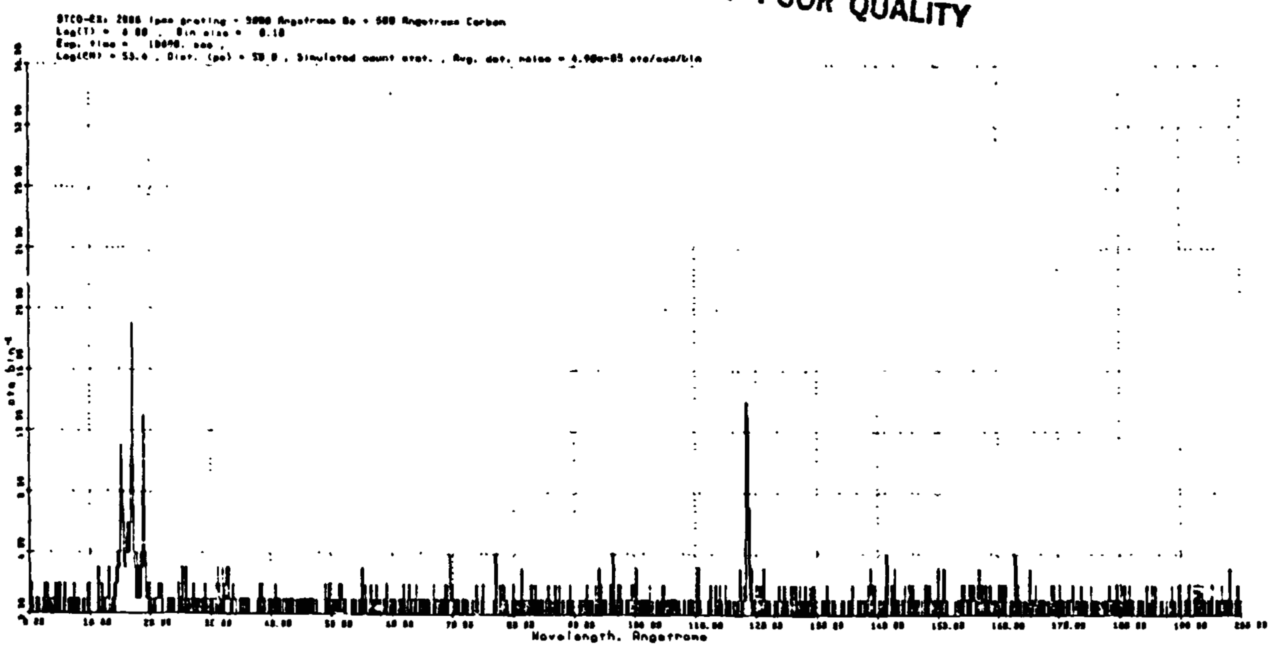

Figure 6: Same as Fig. 5, but now taking the detector noise into account; note that most of the strong lines in the parent source spectrum are detected, but that line intensity ratios cannot be reliably calculated.

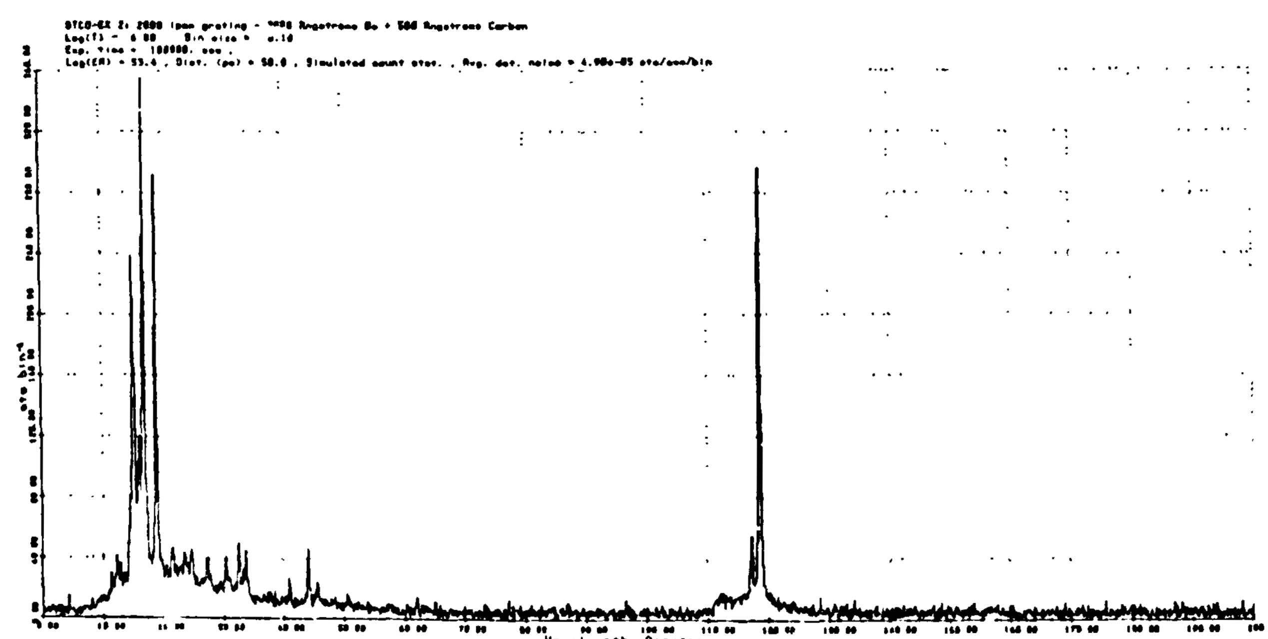

Figure 7: Same as Fig. 6, but for the 4-mirror design at an exposure of 10^5 sec. In this case, the spectroscopic goals discussed in the text are readily within reach; note that the 2-mirror design would lead to somewhat degraded signal-to-noise.