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FUTURE PROSPECTS FOR HIGH RESOLUTION X-RAY SPECTROMETERS

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I. INTRODUCTION

The task I set myself for this meeting was to review and compare the capabilities of the kinds of X-ray spectroscopy payloads I knew about, to compare those with some of my own estimates of the anticipated capabilities of AXAF, and to do this in the context of the science we want to achieve. Let me preface all this by echoing in general terms what many of yesterdays speakers said in detail; namely that Einstein has demonstrated the tremendous scientific power of spectroscopy to probe deeply the astrophysics of all types of celestial X-ray source. However, its limitations of sensitivity and resolution have in most cases permitted us only to whet our appetites. The next generation of spectroscopic instruments can and will provide the banquet.

II. PARAMETERS OF X-RAY SPECTROMETERS

The comparison of alternative types of X-ray spectrometer is extremely difficult because so many orthogonal parameters must be considered and weighed against one another. A probably incomplete list of these includes the energy range, the sensitivity or throughput (which is usually a strong function of energy, E), the degree of background rejection, the resolving power (E/ΔE, also often a function of E), the degree of spatial and spectral multiplex advantage (ability to observe multiple spatial/spectral elements simultaneously), the effectiveness on extended sources (often involving trade-offs of throughput and resolution with field-of-view), the technical difficulty of the instrument and, not least, the size and weight.

a) General Considerations

I will only consider instruments capable of moderate to high spectral resolution ($E/\Delta E > 100$) on discrete celestial sources (but see McCammon's contribution) as the Einstein results demonstrate that this is what is needed for the plasma diagnostics of a source (e.g. Winkler et al. 1981). The state-of-the art then limits us to dispersive instruments. Another clear requirement is that any instrument has some degree of signal concentration so that the detector area (A_D is << the effective collecting area (A_C). This is simply because the lines from all but the strongest sources have fluxes $\lesssim 10^{-3}\text{cm}^{-2}\text{s}^{-1}$, instruments generally have peak efficiencies $\leq 20\%$ and a more or less irreducible particle induced background rate for low-background detectors (achieved in flight by the FPCS and IPC as well as the Wisconsin rocket payload, for example) is $\sim 1 \times 10^{-3}\text{cm}^{-2}\text{s}^{-1}\text{keV}^{-1}$. One needs a concentration factor A_C/A_D just to achieve a signal-to-noise ratio > 1. Of course, with sufficient concentration an instrument becomes signal limited.

Dispersive spectrometers divide into two distinct classes: (i) Bragg spectrometers that use crystal diffractors (like the Einstein FPCS; see Giacconi et al 1979, Canizares et al. 1979) and (ii) spectrometers that use gratings in either transmission (like the Einstein OGS, see Schnopper et al. 1977) or reflection.

The Bragg instruments are capable of high spectral resolution, but they suffer the tremendous shortcoming of having no inherent spectral multiplex advantage. The latter point is crucial, since meaningful plasma diagnostics require at least 4 - 6 line strengths. For Bragg instruments X-rays from a given direction incident on a given cm^2 of Bragg crystal, are reflected only in a narrow passband near the Bragg energy - all others are absorbed. The effective area at a given energy of a Bragg spectrometer is $A_{EFF} = A_{PROJ}\ \eta\ R_C/\Delta\theta$ where A_{PROJ} is the projected area of the diffractor (or telescope in a focal plane instrument), η is the total efficiency of all elements other than the diffractor, R_C is the inherent "integrated reflectivity" of the crystal, and $\Delta\theta$ is the total "acceptance angle" of the crystal (the range of incident angles on the crystal if it is bent or the range through which it is rocked). I assume a uniform area or exposure across $\Delta\theta$. R_C is approximately $\tilde{\sim}\ WR_P$, where W is the "rocking curve width" of the crystal and R_P is its "peak reflectivity", so a near-optimum efficiency (A_{EFF}^{MAX}) is obtained if $\Delta\theta \sim W$. In practice this may not be possible or desirable for various reasons; for example one may want $\Delta\theta$ to be large enough so the corresponding ΔE covers adjacent lines such as the He-like triplets. Selection of a particular $\Delta\theta$ may be one of the design trade-offs. But ultimately all Bragg spectrometers are limited by the limited availability of diffractor materials and so they share the same relevant inherent parameters such as R_C or R_P and $E/\Delta E$ for point sources. For reference the Einstein FPCS had $A_{EFF}^{MAX} \sim 2 - 3\ cm^2$ near 1 keV and up to 10 times less at some energies. The concentration required to reduce background is obtained either with a telescope, or by suitably curving the crystal so it acts as a concentrator/diffractor.

Grating instruments have the spectral multiplex advantage over at least a sizeable part of the energy spectrum. Here concentration is inevitably performed with a telescope. The only truly viable designs I am familiar with call for objective gratings in transmission or reflection. The latter is a relatively new concept for X-ray astronomy (see W. Cash's paper at this meeting). Although focal plane reflection gratings have been discussed at various times in the past, there appears to be no good solution yet to the fundemental limitation of the mismatch between the f/numbers of the grazing incidence telescopes and reflection gratings; telescopes produce ray bundles with angular divergences of $\sim 10^{\circ}$, which is many times larger than the acceptance angle of standard X-ray reflection grating spectrometers.

b) Bragg Spectrometer Design

(i) AXAF Focal Plane Crystal Spectrometer (AXAF FPCS)

Here I assume a scaled up version of the Einstein FPCS. The telescope provides concentration by a factor of $\sim$ 1000 for a point source. The instrument operates in a scanning mode with selectable diffrators to cover the full energy range. It can handle extended sources by virtue of its astigmatic imaging properties, although an aperture should be used to limit the field of view, e.g., to 3 x 30 arc min for the Einstein FPCS. (I do want to note in passing that scanning generally does not limit the time resolution for studies of adjacent lines because the event rate is so low. For $A_{EFF} \sim 10 - 50$ cm^{-2} and line fluxes $\sim 10^{-3}$cm^{-2}s^{-1} there are 20 - 100s per event, and reasonable scan times have negligible effect on the achievable time resolution.)

(ii) Conical Crystal Spectrometer (CCS)

This design is associated largely with Bruce Woodgate and collaborators (Woodgate et al. 1973). A crystal panel is conically curved to give a concentration factor of $\sim$ 100 to a line focus. A given panel can be rocked to cover a moderate energy range ($\sim$ 50%). Larger ranges must be covered by independent instruments. Extended sources must be collimated to ∿ 10' to give $E/\Delta\theta \sim 100$.

(iii) Spherical Crystal Spectrometer (SCS)

This design is due to Schnopper and colleagues (Schnopper and Taylor 1980) and is described fully by Griffiths at this meeting (see also Culhane's presentation). The main difference between this and the CCS is that the bent crystal concentrator (again $A_C/A_D \sim 100$) has a second bend which introduces a pseudo-multiplex advantage at the expense of peak offective area. (e.g. $\Delta\theta$ is >> W by design). Thus the SCS need not be scanned (saving mechanical complexity), and there is a further advantage in the imaging capability (a more subtle point is that the instrument can benefit from the high reflectivity of mosaic crystals without necessarily suffering fully the usually accompanying degradation of energy resolution.) The price one pays is in flexibility. A given fixed panel will cover a $\Delta E/E$ of ∿ 10 - 20%. One cannot bring all the area to bear on a single line nor avoid devoting area to what may be uninteresting portions of the spectrum for some sources. Again, multiple energy ranges require multiple instruments But the extended source capabilities are very good: resolving powers of ≳ 100 can be achieved over a full ½° field.

(iv) Imaging X-ray Spectrometer

This is a "barn-door" objective crystal spectrometer such as the one described by Angel and Weisskopf (1970). I proposed such an instrument with Ken Pounds and collaborators for spacelab. A flat crystal panel is followed by a moderate resolution telescope, which gives a concentration factor of ∿ 10^5 for a point source and full field imaging over nearly 1°. Thus this instrument has a significant spatial/spectral multiplex advantage.

At a single setting one obtains a full image in a narrow band whose central energy varies along one dimension . The crystal must be rocked to build up a spatially resolved spectrum over the whole image. The flat crystal panel can yield higher resolutions than bent crystal spectrometers over its spectral range (like the SCS it can get high resolution with mosaic crystals), and unlike the other instruments its resolution is not degraded by source extent.

c) Grating Spectrometer Designs

(i) AXAF Transmission Gratings Spectrometer (AXAF TGS)

Although results from the Einstein OGS have been slow in coming, the instrument did acquire some remarkable spectra, and significant improvements have been made in grating fabrication since the HEAO program at Utrecht, MPI and MIT. EXOSAT has a grating system and gratings are under consideration for other missions (e.g. ROSAT reflight). I will concentrate on the parameters of a possible AXAF OGS, but any similar system would share many of the same properties. The concentration factor of such a system for a point source is $10^6 - 10^7$ because of the small image size.

As a slight digression let me describe some of the improvements in grating fabrication being made at MIT. This is work of Prof. Henry Smith of our Electrical Engineering Department, with whom I and Mark Schattenburg are collaborating to perfect gratings of high spatial frequency. We have been particularly interested in making thick gratings for use around the 6 keV iron lines using the technique of soft X-ray lithography perfected by Smith and his co-workers at MIT and Lincoln Lab. Figure one shows the calculated, one-sided first order efficiency for an 0.9 μm thick grating. This acts as a phased grating in the region of interest giving ultimate peak two-sided efficiencies of 50%. That such gratings are feasible is shown in Figure 2, which is an electron micrograph of a

3000 lpmm gold grating of thickness 0.6 μm. The gratings are all mounted on polyimide substrates (taken into account in Fig. 1) that make them extremely rugged. Of course at lower energies the gratings should be free-standing. A 5000 lpmm grating has been made and we are presently pushing for increasing the thickness to the desired value.

Transmission gratings in coma-corrected mountings (Beuerman et al. 1978) could give very high throughput and resolution ($E/\Delta E \sim 100 - 600$) for point sources. They would even be useable on extended sources in which most of the flux is in a few emission lines. This is indeed the case for many supernova remnants. The remnants in the LMC are particularly well suited to this because of their small size, and cooling cores in galaxy clusters may be similarly accessible.

(ii) Objective Reflection Grating Spectrometer (ORGS)

This clever design is discussed in detail by Cash (this meeting). The concentration factor is $\sim 10^5$ for point sources. For extended sources one needs rather fine collimation (1' x 20') to avoid degradation of the resolution to below $E/\Delta E = 100$, and this will both add complexity and limit the signal on extended sources such as SNR's and clusters. The ORGS has great promise, but as the youngest of the instruments mentioned here it naturally has the highest degree of undemonstrated technology at this time.

III. COMPARATIVE ANALYSIS

A comparison of the performance of the various spectrometer designs is extremely difficult and fraught with pitfalls. Each design contains enough free parameters that it is nearly always possible to improve one characteristic at the expense of another (e.g., A_{EFF} at some energy at the expense of energy range). Thus only hard and fast designs can be compared in any detail. Nevertheless, it is instructive to analyze the relative merits of several "strawman" instruments. I do so with apologies to the various proponents of each instrument and with the warning that the parameters listed below can change by factors of up to 10 as the designs are modified.

I have made various assumptions in computing Tables 1 and 2. The AXAF parameters are estimated from various AXAF working group papers. For the crystal instruments (CCS, SCS, IXS) I assume crystal projected areas of $10^3 \mathrm{cm}^2$ and diffractor properties appropriate to TAP (1 keV) or LiF (6.7 keV). For the ORGS and IXS I take telescope effective areas of 500 cm^2 at 1 keV (and zero at 6.7 keV). I assume all detector efficiencies are 1.0. Collimator transmission is taken as 0.7 for the CCS and 0.5 for the ORGS. The SCS is assumed to have $\sim$ 150 spectral resolution elements that span the 5 lines in question (e.g. it has pseudo spectral multiplex advantage). I take the weak source limit in which the background is all of non-X-ray origin with flux $10^{-3} \mathrm{cm}^{-2} \mathrm{s}^{-1} \mathrm{keV}^{-1}$. I assume that the CCS like the FPCS can measure this background simultaneously with the signal in unilliminated portions of the position sensitive detector (as we have done with the Einstein FPCS). The 20' source is assumed to have uniform surface brightness, so that apertures reduce the flux to the instrument.

The listed 3σ flux limits are for each of five lines (to allow some plasma diagnostics) and a total exposure of 5×10^5 s. Of course, the multiplexed instruments will get information about the entire spectrum simultaneously. This is of greater value near 1 keV than near 7 keV, as there are many more lines near the former energy. Except where indicated the instruments are signal limited and so the number of detected photons is very small.

IV. CONCLUSIONS

One immediate conclusion is that each of the straw-man instruments has a sensitivity that is at least an order of magnitude better than that of the Einstein FPCS. This means that the next generation of instruments is sure to provide the spectral banquet I referred to in §1. For illustration I show in Table 3 some crude estimates of the typical line strengths for a given class of objects (i.e., not just the brightest one or two). With limiting fluxes of 10^{-5} to $10^{-6}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ one will have many hundreds of galactic and extragalactic objects to study.

A second conclusion is that each instrument involves trade-offs and compromises that must be weighed with great care. Even my crude analysis shows how strongly the relative merits of a given design depend on the details of the objective (e.g. extended vs. point sources). I have not even addressed important details such as how the resolution degrades with source extent or how sensitive the instrument may be to spacecraft pointing uncertainties.

A third conclusion is that AXAF promises to have a powerful spectral capability when it is eventually launched. Probably the greatest weakness of the two AXAF instruments considered here is the at least partial breakdown of the multiplexed TGS for sources > 20" in extent. It would seem that this leaves a major hole for some other future mission, especially around the Fe line where the effective area of the FPCS is severely limited by the telescope efficiency.

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REFERENCES

Angel, J.R.P. and Weisskopf, M.C. 1970, Astron.J., 75, 231.

Beuerman, K.P. et al. 1978, Applied Optics, 17, 2304.

Canizares, C.R. et al. 1979, Ap.J., 234, L33.

Giacconi, R. et al. 1979, Ap.J., 230, 540.

Schnopper, H.W. et al. 1977, Applied Optics, 16, 1088.

Schnopper, H.W. and Taylor, P.O. 1980, Applied Optics, 19, 3306.

Winkler, P.F. et al. 1981, Ap.J., 246, L27.

Woodgate, B.E. et al. 1973, Applied Optics, 12, 2759.

TABLE 1

WEAK SOURCE FLUX LIMIT FOR DETECTION OF 5 LINES AT 1 keV IN 5×10^4s.

	A_{EFF}^{MAX}	A_{DET}^{POINT}	FOV	I_{MIN} (cm^{-2}s^{-1})	
INSTRUMENT	(cm^2)	(cm^2)	(arc min)	POINT	20'
AXAF FPCS	340(a)	1	3' x 30'	3×10^{-6}	3×10^{-5}(b)
CCS	240(a)	10	10' x 5°	1×10^{-5}(b)	4×10^{-5}(b)
SCS	2	0.02	30' x 5°	1×10^{-4}	1×10^{-4}
IXS	170	0.005	1° x 1°	6×10^{-6}	4×10^{-5}
AXAF TGS	200	10^{-4}	-	1×10^{-6}	(C)
ORGS	75	0.005	1' x 20'	2×10^{-6}	2×10^{-4}

Notes:

a. No multiplex advantage; I_{MIN} assumes 10^4s each on 5 lines.

b. Sensitivity is background limited at 10^4s.

(C) Extended source capability for sources < 20" and strong emission line sources. Deconvolution possible on other sources.

TABLE 2

WEAK SOURCE FLUX LIMIT FOR DETECTION OF 5 LINES AT 7 keV IN 5 x 10^4s

INSTRUMENT	A_{EFF}^{MAX} (cm^2)	A_{DET}^{POINT} (cm^2)	FOV (arc min)	I_{MIN} (cm^{-2}s^{-1}) POINT	20'
AXAF FPCS (a)	20	1	3' x 30'	$5 \times 10^{-}5$	4×10^{-4}(b)
CCS (a)	140	10	10' x 5°	2×10^{-5}(b)	4×10^{-5}(b)
SCS	4	.02	30' x 5°	5×10^{-5}	5×10^{-5}
AXAF TGS	50	10^{-4}	1' x 20'	4×10^{-6}	(c)

Notes:

(a) No spectral multiplex advantage; I_{MIN} assumes 10^4s each on 5 lines.

(b) Sensitivity is background limited.

(c) Extended source capability for sources < 20" and strong emission line sources. Deconvolution possible on other sources.

TABLE 3

ESTIMATED LINE FLUXES FOR CLASSES OF ASTROPHYSICAL OBJECTS

LINE FLUX ($cm^{-2}s^{-1}$)	SIZE		
	< 10"	∿ 1'	∿ 20'
10^{-2}			
	• BINARIES (Fe LINES)		• SNR
10^{-3}		• LMC SNR	
		• COOLING CLUSTER CORES	• CLUSTER Fe LINES
	• STELLAR CORONAE		
10^{-4}	• AGN		
10^{-5}	• GAS IN GALAXIES (e.g. M86)		
10^{-6}	• CLUSTERS @ $Z = 0.5$		

FIGURE CAPTIONS

Figure 1: Calculated one-sided first-order efficiency for the illustrated gold transmission grating on a polyimide substrate.

Figure 2: Electron micrograph of a 3000 lpmm gold grating on a polyimide substrate. The grating thickness is 0.6 μm plus 1.0 μm of polyimide. This grating was fabricated by a multistep process involving both holographic exposure and soft X-ray lithography.

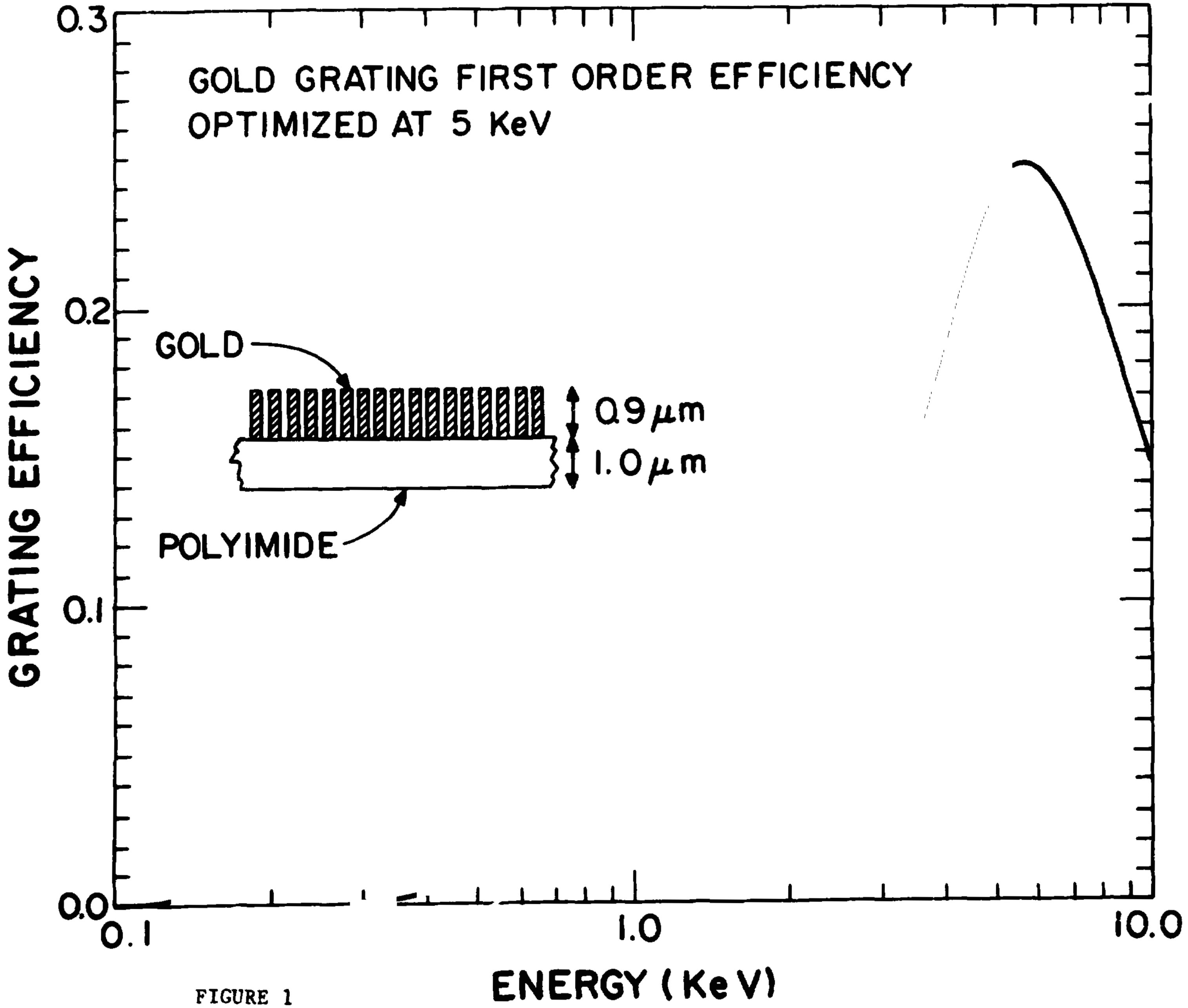
GOLD GRATING FIRST ORDER EFFICIENCY
OPTIMIZED AT 5 KeV
GOLD
0.9 μm
1.0 μm
POLYIMIDE
GRATING EFFICIENCY
0.3
0.2
0.1
0.0
0.1
1.0
10.0
ENERGY (KeV)

FIGURE 1

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

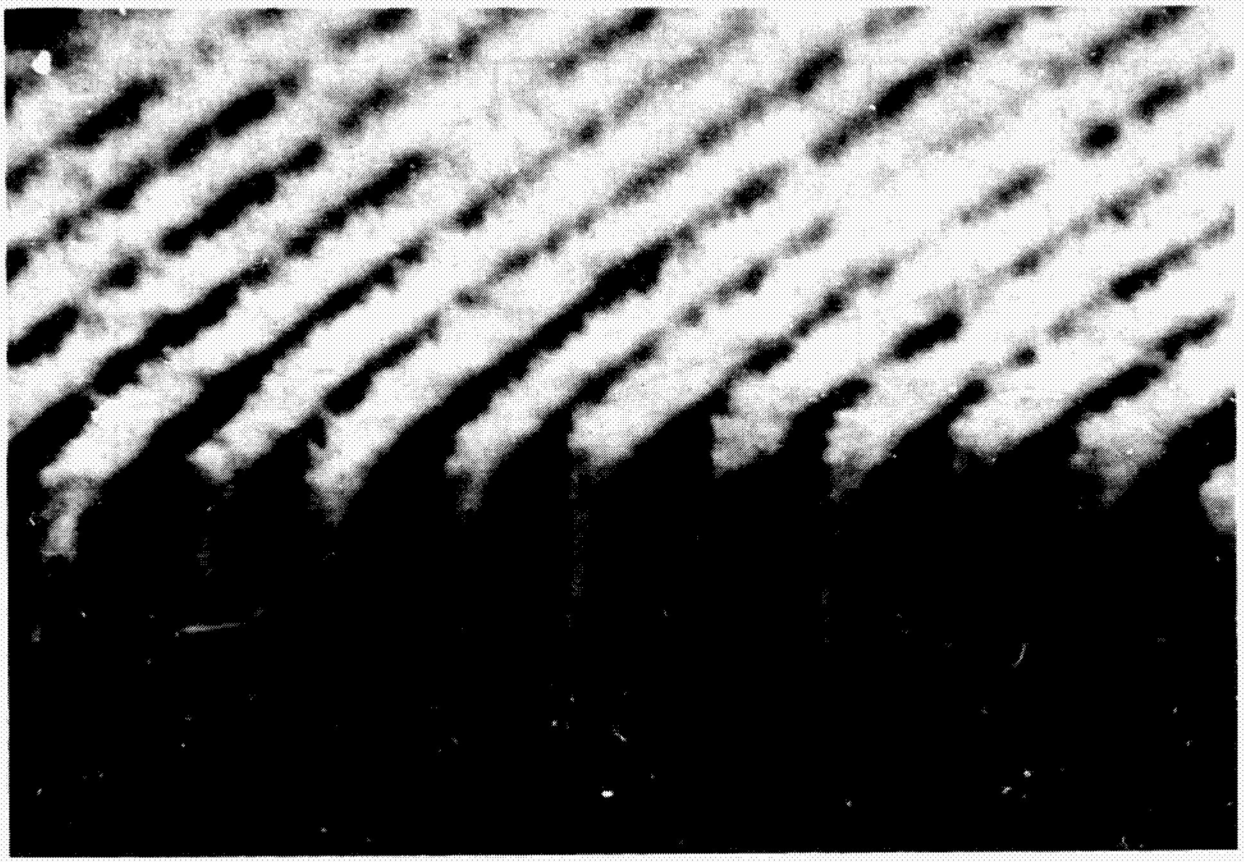

FIGURE 2.