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LUMINESCENCE OF APOLLO 11 AND 12 LUNAR SAMPLES

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Abstract--Luminescence measurements have been made of Apollo 11 and 12 samples with far, middle, and near u.v., X-rays, and protons. Efficiencies were found to be low, of the order of 10^{-6} or less, for all irradiations. These cannot account for the astronomical observations of luminescence on the moon, at least not in the Apollo 11 and 12 landing areas and at least to the extent that our samples are representative (we do not have, however, any sialic rocks, as 12013, among our samples). In general, the efficiencies agree well with those for terrestrial rocks in which efficiency decreases with increasing basic character. We could find no evidence from measurements of both interior and exterior specimens that micrometeorite impact, space radiation, and other mechanisms operating at the lunar surface have affected the luminescence character of the rocks. Such effects are too small to be seen in our present series of measurements because of low luminescence efficiency and consequent weak signal.

INTRODUCTION

We have reported the first results of our luminescence studies of the Apollo lunar samples in previous papers (GREENMAN and GROSS, 1970a, 1970b); in this paper we present additional results of measurements of the Apollo 11 samples together with the first results of measurements of the Apollo 12 samples. To recapitulate briefly, our objectives in these luminescence studies are (1) to understand how the luminescence behavior reflects the origin, history, and environment of the lunar rocks, (2) to discover luminescence characteristics of the lunar rocks that might aid in geologic mapping and other lunar exploration activities, and (3) to evaluate the reports of luminescence on the moon based on astronomical observations.

To achieve these objectives, we are measuring the luminescence spectra and efficiencies and comparing the results with those of similar measurements of terrestrial rocks and minerals. Our excitation sources are those of importance in the space environment--u.v. (1216 and 2000-4000 Å), X-rays (0.2-8 Å), protons (up to 150 keV), and electrons (up to 150 keV)--and our measurements of the luminescence spectra are from around 1216 Å (or from the exciting wavelength if it is longer than 1216 Å) to 6000 Å, except that in cases where luminescence is found near 6000 Å we extend the measurements to the cutoff wavelength of the detector, near 8000 Å.

EXPERIMENTAL PROCEDURE

The experimental arrangements for the various irradiations are shown in Figs. 1-3. The system for middle and near u.v. irradiation was modified in some respects from that described in our previous papers in that a Bausch and Lomb grating monochromator was substituted for the Gaertner quartz prism monochromator for obtaining a single line or band, light-collecting and focusing optics were added at the entrance and exit slits of the Jarrell Ash output monochromator, and a photon-counting system of signal measurement was added. Also, an argon ion laser with a u.v. generator, which gave a line at 2573 Å, was used for one series of measurements.

The light-collecting and focusing optics were also used in the far u.v. measurements; otherwise this system was the same as previously described.

The samples used in the measurements are as follows:

Apollo 11: 10044-38 (exterior) and 10044-53 (interior), coarse-grained igneous

10022-55 (exterior) and 10057-45 (interior), fine-grained igneous

10048-36 (interior) and 10048-37 (exterior), breccia

Apollo 12: 12002-99 (interior), 12002-106, 107 (interior), and 12002-114 (exterior), medium-grained olivine dolerite

12020-54 (interior) and 12020-55 (exterior), fine-grained olivine basalt

Terrestrial: Granite (California), gabbro (California), willemite (New Jersey), andesine (Norway)

The efficiencies given in the following section are total efficiencies; that is, they represent the ratio of energy in the luminescence band to the energy incident upon the sample.

DATA ANALYSIS AND RESULTS

Middle and near u.v. irradiation with xenon-mercury arc lamp

The results obtained from the Apollo 11 samples with 3000 Å irradiation were reported in our previous papers. The luminescence signals, if present at all, were weak and indicated upper limits of efficiency from 5×10^{-6} to 2×10^{-5}. In the present series of measurements, we irradiated the Apollo 12 samples with 3000 Å and both the Apollo 11 and 12 samples with 3650 Å and 2516 Å. In this last case, other lines were present in the incident beam, the 2516 Å line accounting for about half the flux and lines at 2800, 2900, 2970, 3000, 3140, 3340, and 3650 Å together accounting for the other half. Except for the willemite, none of the samples gave a detectable luminescence signal so that we have no basis for revising the efficiency upper limits already reported.

Middle u.v. irradiation with laser

The 2573 Å line from an argon ion laser was used in this series of measurements. Lunar sample 12020-54 showed a luminescence band in the region 6198-7765 Å above the $BaSO_4$ reference level, although the signal was only slightly above the noise (Fig. 4). Granite gave a detectable band at 6375-7820 Å, gabbro a marginally detectable band at 6280-7120 Å, and willemite a pronounced peak at about 5316 Å with a secondary peak at 7638 Å. Similar red luminescence bands had been found earlier in various silicates by GROSS and HYATT (1970) when they irradiated with the 4480 Å line from the argon laser, although the efficiencies were lower than with the 2573 Å line. The results of the 2573 Å irradiation, together with preliminary values for the upper limits of the efficiency, are summarized in Table 1.

Table 1. Luminescence data for samples irradiated with 2573 Å from an argon ion laser

Sample	Peak wavelength (Å)	Bandwidth* (Å)	Efficiency upper limit at peak wavelength	Efficiency upper limit of total band
Willemite	5316	424	4×10^{-5}	1×10^{-2}
	7638	407	1×10^{-7}	3×10^{-5}
Granite	7169	1190	4×10^{-9}	4×10^{-6}
Gabbro	6700	655	2×10^{-9}	1×10^{-6}
12020-54	6826	915	2×10^{-9}	2×10^{-6}

*Full width at half maximum

Far u.v. through visible irradiation with hydrogen discharge

These measurements were made to observe the luminescence effect of hydrogen Lyman-alpha. Total band irradiation was used first before attempting measurements with the hydrogen Lyman-alpha line alone. The results are shown in Figs. 5-7. Sample 10057-45 shows distinct luminescence in the band 2260-4363 Å with a peak around 3140 Å. Gabbro shows an almost identical band. In the remainder of the samples there are indications of a broad red band in the Apollo 11 and terrestrial samples and a narrower red band in the Apollo 12 samples. That these signals are real, though weak, is supported by the presence of red bands with the laser, X-ray, and proton irradiations. Calibration of the system is still in progress so that no efficiency values are yet available.

X-ray irradiation

The X-rays for these measurements were obtained from a tungsten target; the tube was operated at 70 kV and 45 mA. Under these conditions the irradiation band was from about 0.2 Å to the cutoff of the beryllium window at 8 Å. Distinct luminescence spectra were obtained from willemite, granite, and gabbro in the band from about 4000 Å to near 8000 Å. No detectable luminescence was found in the lunar samples in this band, and none was found in any of the samples in the band from 1000 Å to 4000 Å. The gabbro and lunar samples 10044-53 and 12020-55 were also measured with the source-to-sample distance reduced by about 30 per cent; this resulted in an increase of about 50 per cent in the intensity of the gabbro spectrum and no change in that of 12020-55. The curve for 10044-53, however, showed a barely discernible rise with a maximum in the 5300-5800 Å range. The granite and gabbro curves (Figs. 8 and 9) display prominent peaks at 5800 Å and at about 7350 Å and a third very faint peak at about 4800 Å in granite and about 4850 Å in gabbro. The curve for willemite was found to be virtually identical to the one obtained with u.v. irradiation--a single peak at 5350 Å and a band width of 550 Å at full width, half maximum. Preliminary efficiency calculations are shown in Table 2.

Proton irradiation

In this irradiation we used protons of 5 keV energy and a proton flux density at the sample of 2.0×10^{14} protons/cm^2 sec 5 keV, or an energy flux density of 1.6×10^6 ergs/cm^2 sec. As the protons were extracted from an RF-excited glow discharge of hydrogen, we ran a glow discharge reflectance curve for each sample before turning up the accelerating voltage to bombard with protons. With the accelerating voltage turned up, we also ran curves from an aluminum mirror, a non-luminescent material, to determine whether for any reason changes in the reflected light level occurred under conditions of bombardment by the proton beam. In all cases, the reflected light due to the glow discharge was below the dark current of the sensor except for the strong atomic hydrogen lines at 4861 Å and 6563 Å.

Comparison of the glow discharge reflectance curve with the proton irradiation curve for each sample showed that all samples displayed luminescence over a very broad band. A typical set of curves, with the wavelength limits so determined indicated by the numbered arrows, is shown in Fig. 10. In addition, most samples show a narrow line feature in the 5950-6000 Å interval. Willemite, 10044-38, and perhaps 10057-45 do not have this line; $BaSO_4$ has such a line at 5600 Å. The source of this feature has not yet been determined. Calibration is still in progress so that efficiency values are not yet available.

Table 2. Luminescence efficiencies of terrestrial and lunar samples with X-ray irradiation

Sample	Efficiency	Remarks
Willemite	4×10^{-3}	
Granite	2×10^{-4}	Total for all three bands
Gabbro	6×10^{-5}	Total for all three bands
All lunar samples	$<5 \times 10^{-6}$	Based on minimum detectable signal with source-to-sample distance used
10044-53	8×10^{-7}	With reduced source-to-sample distance

A second set of measurements was made with protons of 100 keV energy at 8 x 10^{-6} A, for a proton flux density of 10^{13} protons/cm^2 sec 100 keV, or an energy flux density of 1.6 x 10^6 ergs/cm^2 sec. The luminescence in this case was measured over the range 1000-4000 Å. In all cases, the flash effect described by NASH (1966), in which an initially high signal decays rapidly in a matter of minutes, was observed. NASH and GREER (1970) also observed this effect in most Apollo 11 samples. Repeated runs showed that the signal leveled off after about 6 to 9 minutes so that the efficiency values given below are for the last rather than the first runs.

Granite and gabbro show a low peak at 2220 Å and a prominent peak at 2760 Å, with a barely discernible peak at 3140 Å. The lunar samples are similar except that the 3140 Å peak is much more prominent. Also, in some lunar samples, the decay rates of the 2760 Å and 3140 Å peaks appear to be different, the former peak being most intense initially but declining more rapidly such that the latter is most intense in the stabilized luminescence curve. Efficiencies for the 100 keV proton irradiation in the 1000-4000 Å band are shown in Table 3.

DISCUSSION

The luminescence efficiencies of the lunar samples, despite some variation with irradiation type, are uniformly low. They cannot, therefore, account for the astronomical observations of luminescence on the moon, at least not in the Apollo 11 and 12 landing areas, if our samples are representative and if our laboratory irradiation conditions do not differ radically from those at the surface of the moon (GREENMAN and GROSS, 1970b; NASH and GREER, 1970). It should be observed, however, that rocks of more sialic character must exist on the moon, as evidenced by Apollo 12 rock 12013, but rocks of this type are not

Table 3. Luminescence efficiencies of terrestrial and lunar samples in the 1000-4000 Å band with 100 keV proton irradiation

Sample	Efficiency
Granite	2×10^{-7}
Gabbro	5×10^{-8}
10022-55	9×10^{-9}
10044-53	1×10^{-8}
10048-36	1×10^{-8}
12002-114	8×10^{-9}
12020-55	1×10^{-8}

represented among our samples. Such types can be expected to show higher luminescence efficiencies if they behave at all like their terrestrial counterparts (GREENMAN *et al.*, 1965; GREENMAN and MILTON, 1968; NASH, 1966).

We could find no evidence from measurements of both interior and exterior specimens and of the various lunar lithologic types that meteorite and micrometeorite impact, space radiation, and other processes operating at the lunar surface have affected the luminescence character of the rocks. SIPPEL and SPENCER (1970) report luminescence differences in the Apollo plagioclases both with respect to terrestrial plagioclases and with respect to degree of shock damage. They were working with individual grains under the microscope, however. We measure the whole rock, and under these circumstances the significant content of non-luminescent material greatly lowers the rock efficiency, as opposed to the mineral efficiency. This lowering is great enough to mask the effects noted by SIPPEL and SPENCER. The low efficiency and consequent weak signal have also masked the presence of degraded spectra, described by NASH and GREER (1970), in this series of measurements.

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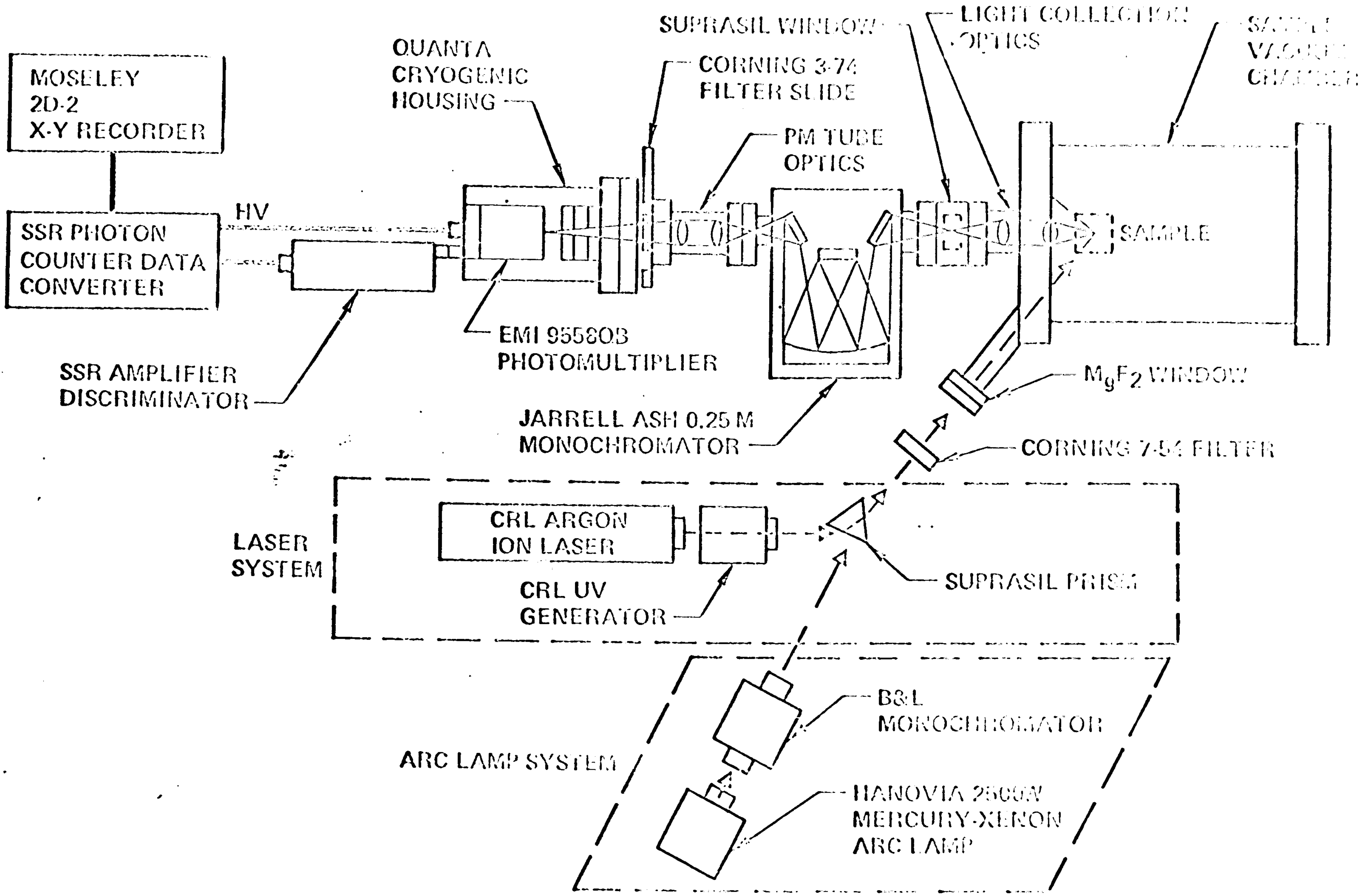
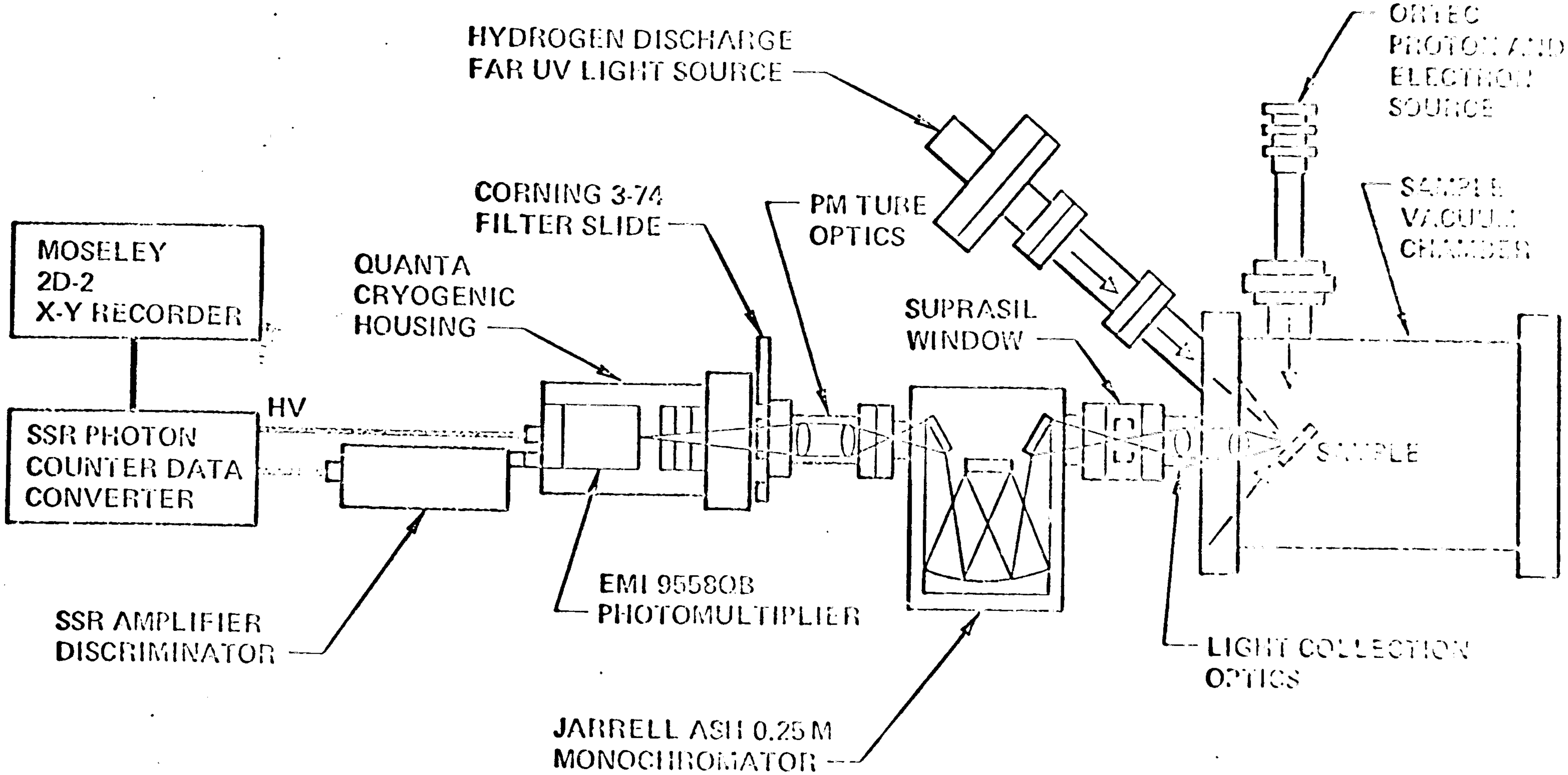


LUMINESCENCE MEASUREMENT SYSTEM FOR FAR UV
AND 0-5 keV PROTON AND ELECTRON IRRADIATION



LUMINESCENCE MEASUREMENT SYSTEM FOR SOFT X-RAY AND 0-150 keV PROTON AND ELECTRON IRRADIATION

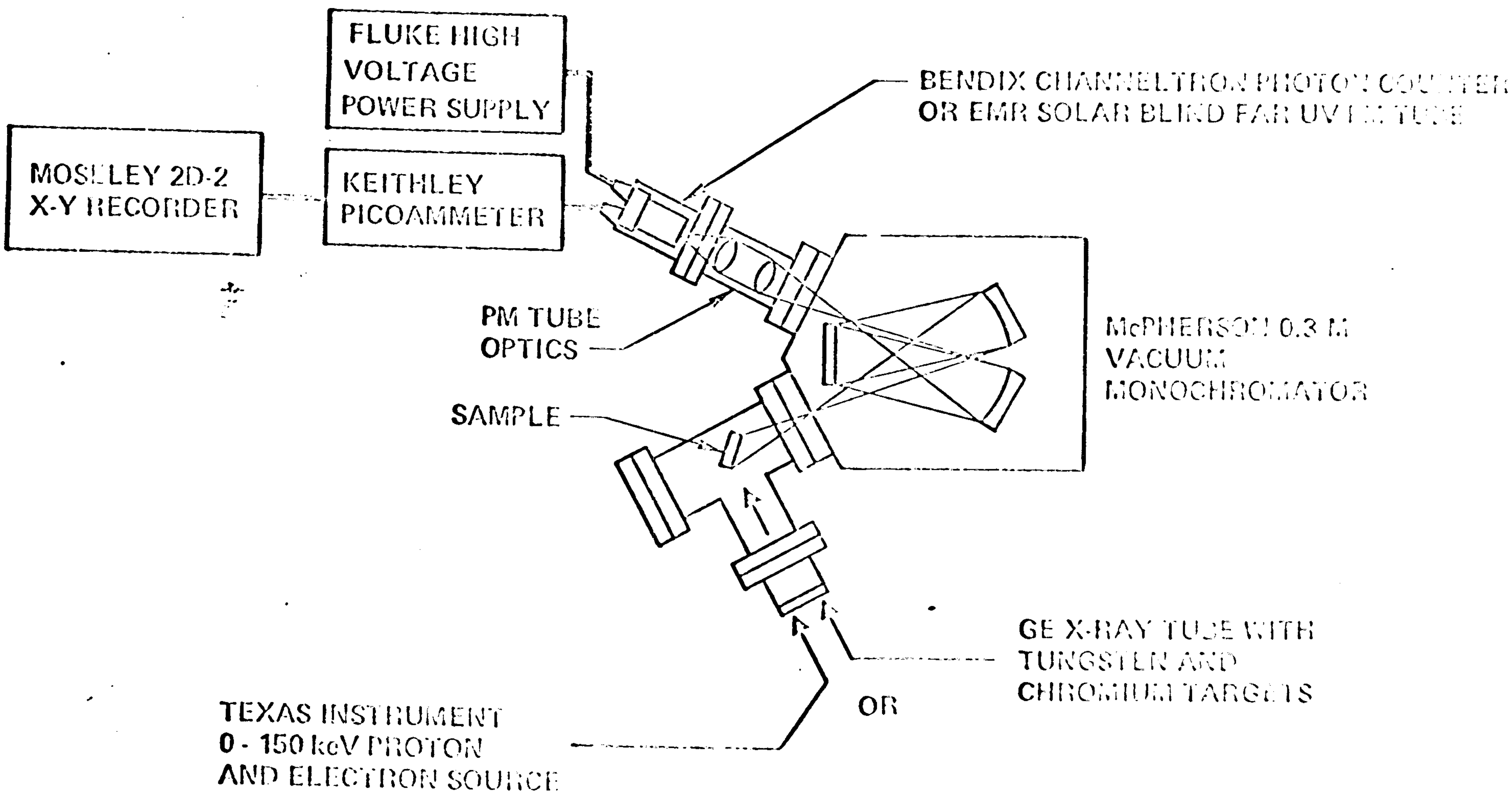


Fig. 3

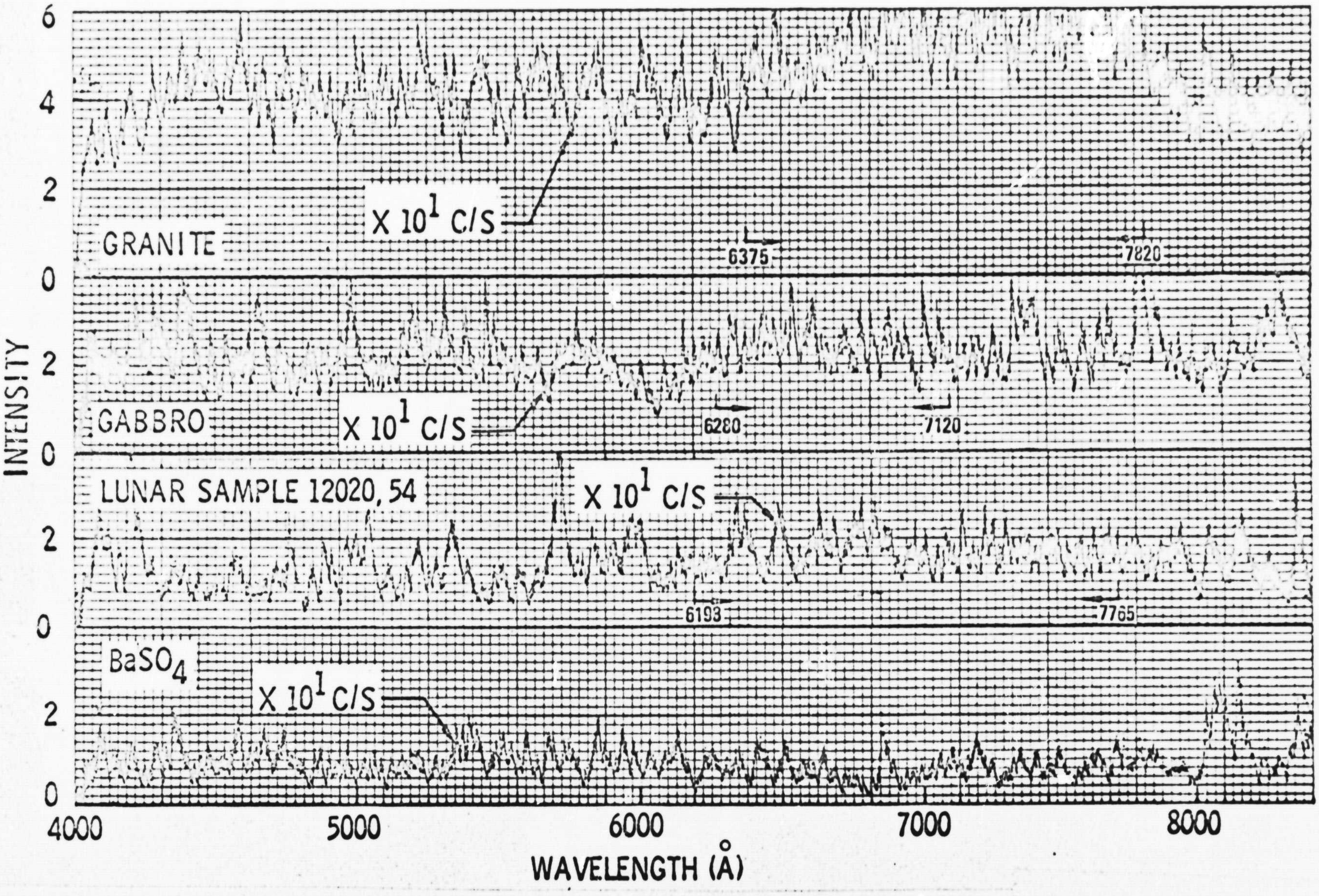


Fig. 4 GREENMAN AND GROSS MS #179

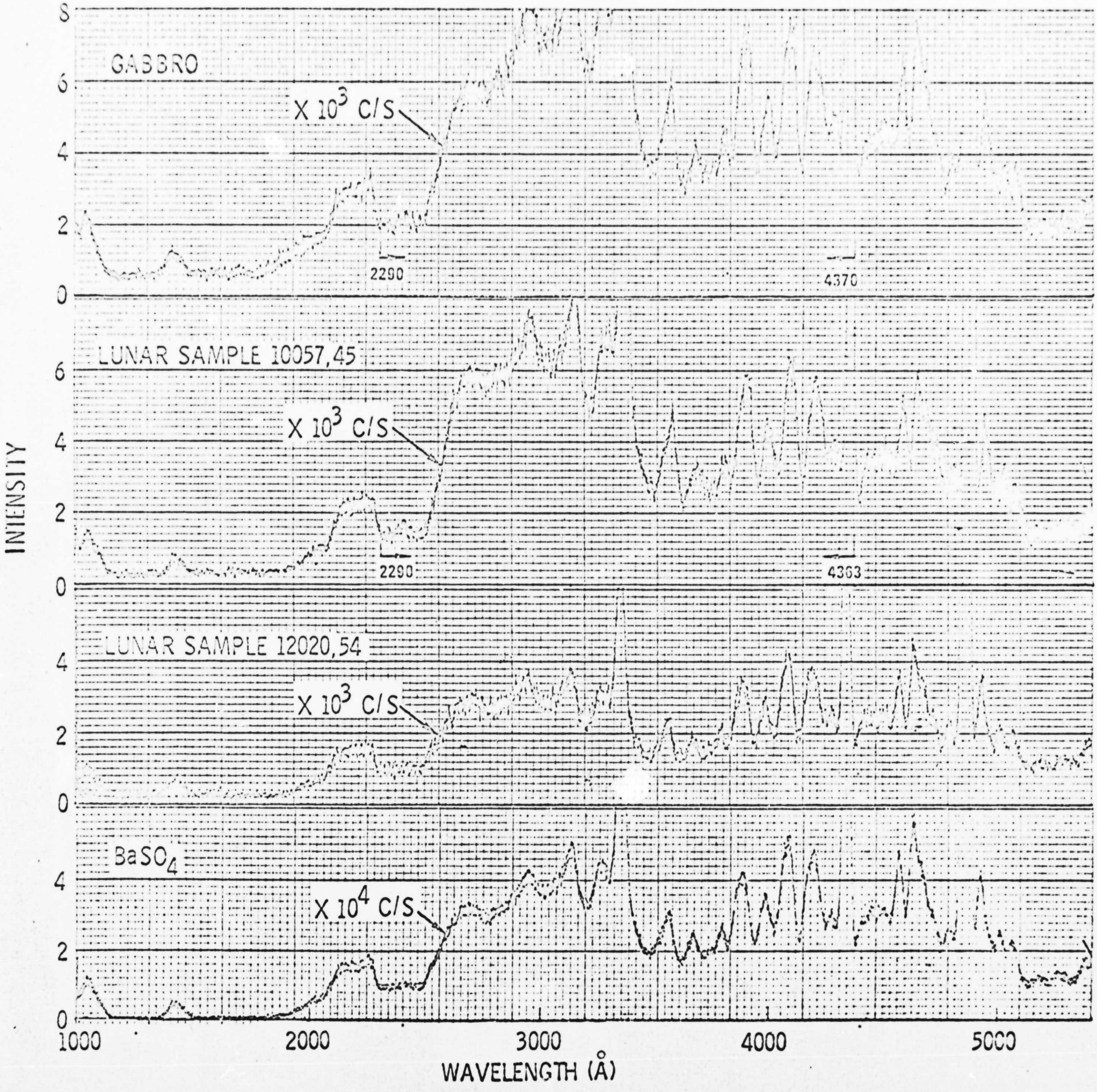
Fig 5

LUMINESCENCE (1800-4500Å) INDUCED BY HYDROGEN DISCHARGE IRRADIATION (1120Å THROUGH VISIBLE)

APOLLO 11 AND 12 AND EARTH SAMPLES

JARRELL-ASH: 3000 Å BLAZE GRATING

EMI 9558QB (PHOTON COUNTING MODE)



POSSIBLE LUMINESCENCE (4000-8000Å) INDUCED BY HYDROGEN DISCHARGE IRRADIATION (1120Å THROUGH VISIBLE)

APOLLO 11 AND WILLEMITE SAMPLES

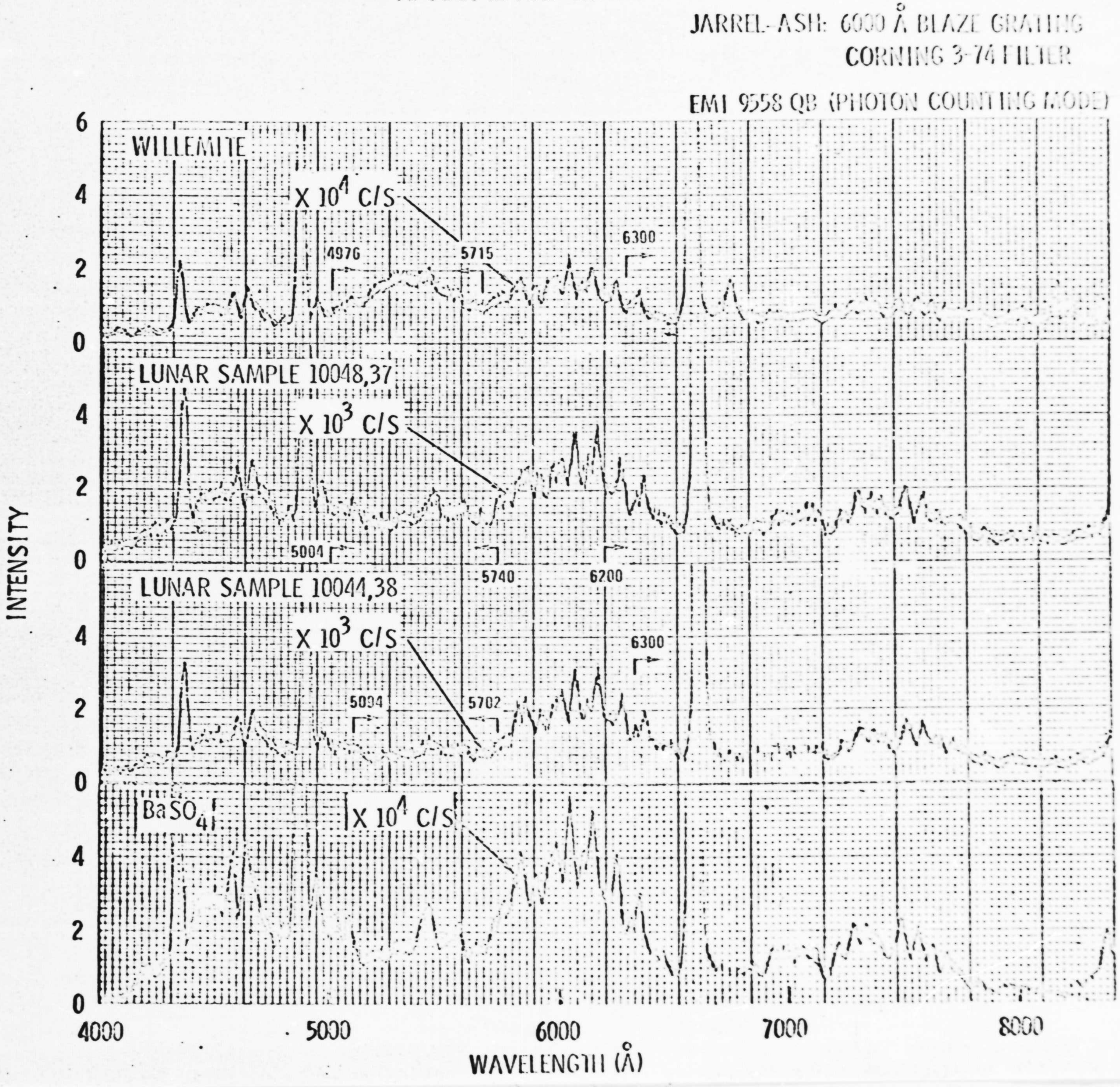


Fig 6

Fig 7

POSSIBLE LUMINESCENCE (4000-8000Å) INDUCED BY HYDROGEN DISCHARGE IRRADIATION (1120Å THROUGH VISIBLE)

APOLLO 12 AND GRANITE SAMPLES

JARRELL-ASH: 6000 Å BLAZE GRATING
CORNING 3-74 FILTER

EMI 9558QB (PHOTON COUNTING MODE)

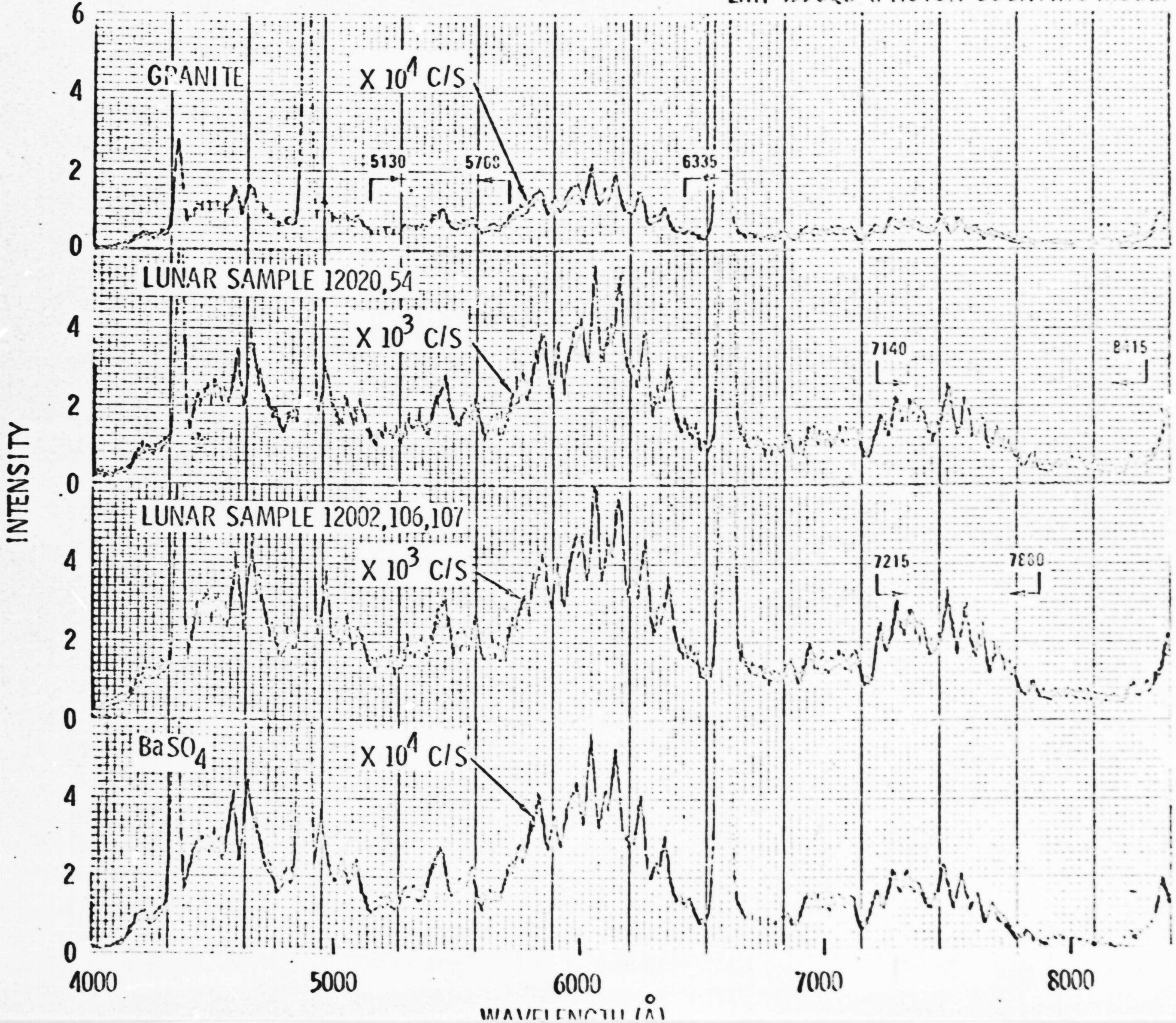


Fig 7

Fig 8

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LUMINESCENCE OF GRANITE WITH X-RAY IRRADIATION

(TUNGSTEN TARGET, 70kV, 45mA)

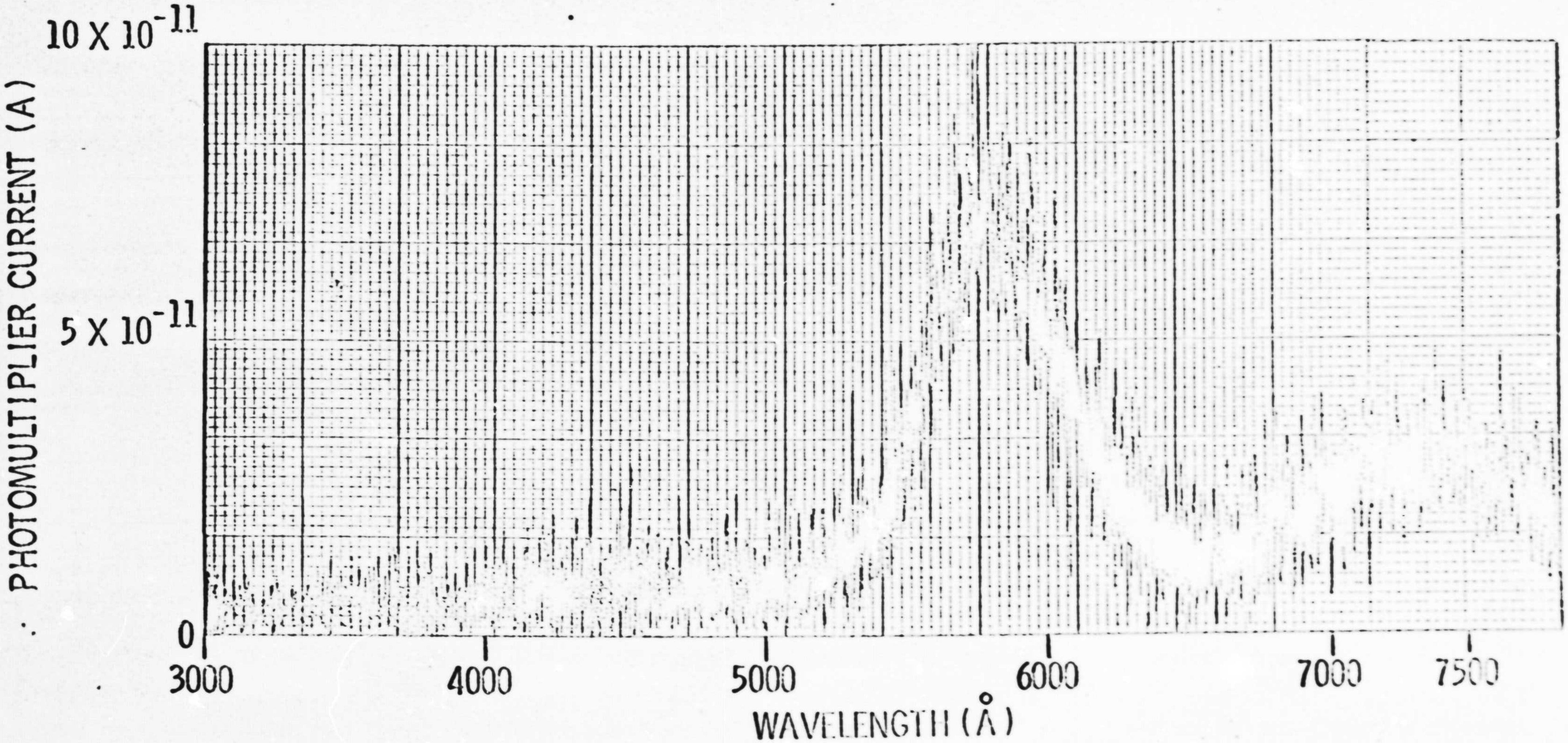


Fig. 8

Fig 9

18478

LUMINESCENCE OF GABBRO WITH X-RAY IRRADIATION

(TUNGSTEN TARGET, 70kV, 45mA)

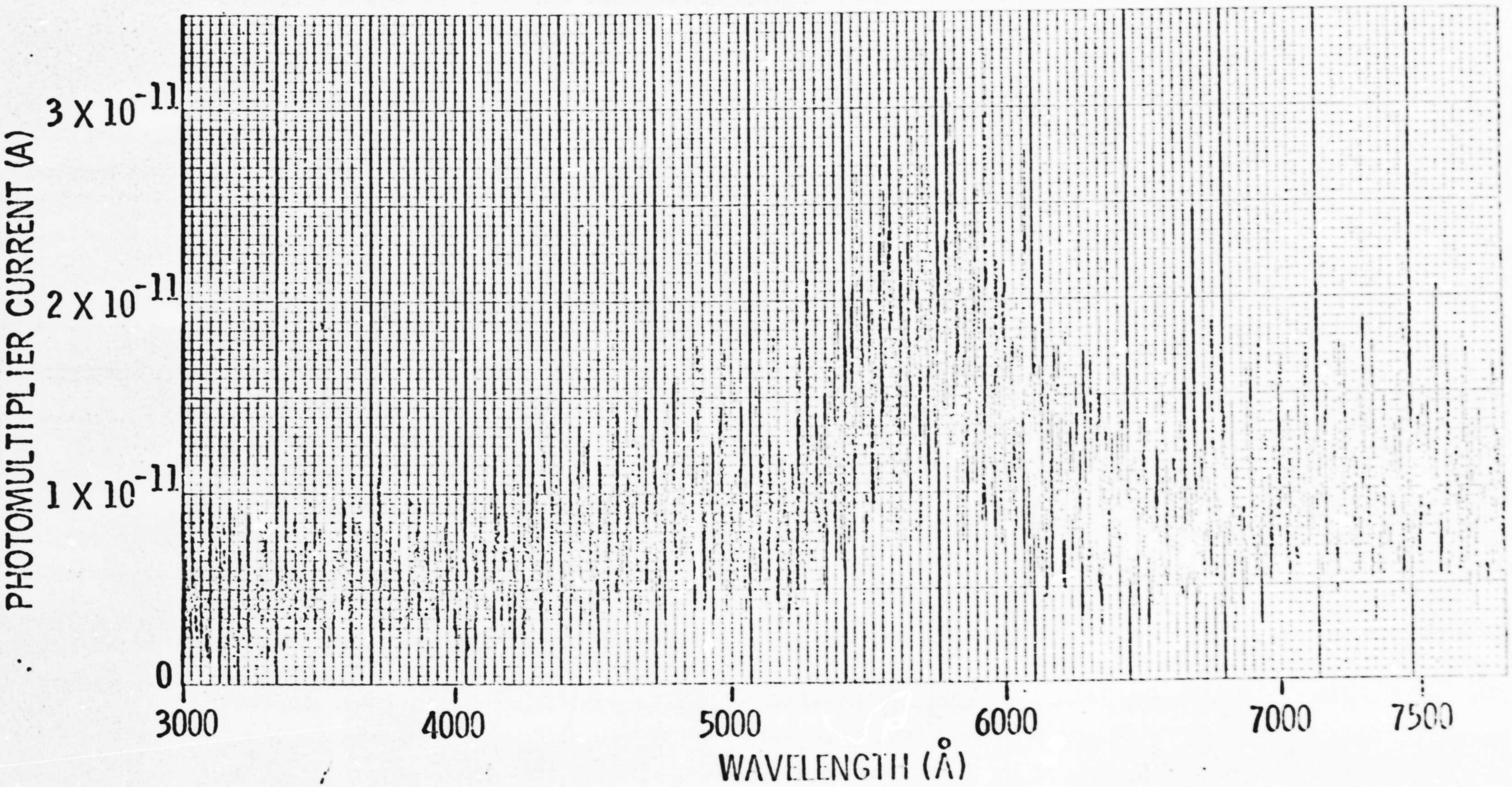
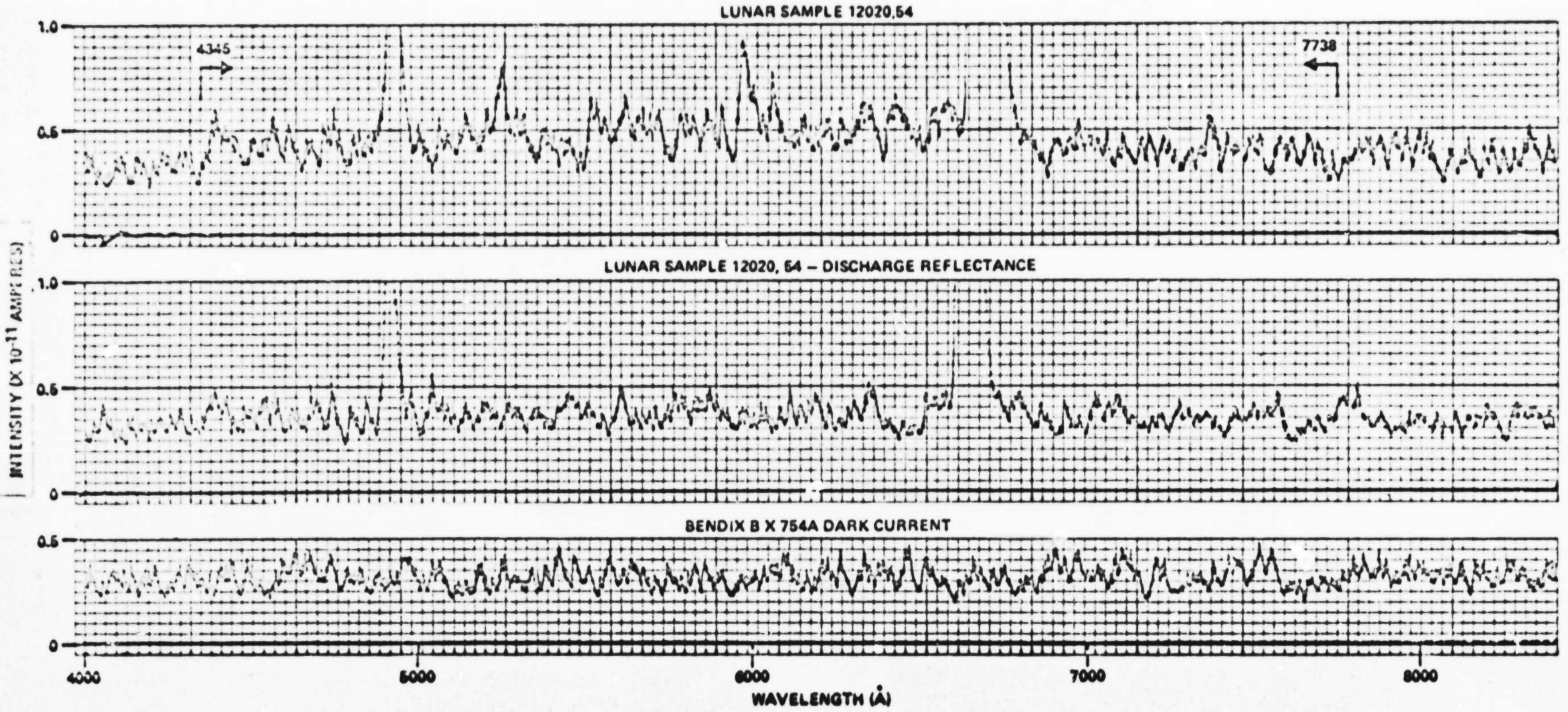


Fig. 9

Fig. 10



LUNAR SAMPLE 12020,54
4345
7738
LUNAR SAMPLE 12020, 54 – DISCHARGE REFLECTANCE
BENDIX B X 754A DARK CURRENT
INTENSITY (X 10^-11 AMPERES)
1.0
0.5
0
4000
5000
6000
7000
8000
WAVELENGTH (Å)