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X-RAY CONTINUA AND LINE SPECTRA FROM HIGHLY STRIPPED ATOMS IN A MAGNETICALLY COMPRESSED PLASMA*

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A single-crystal x-ray spectrometer has been constructed and applied to the study of the x-ray spectrum emitted from the deuterium plasma in the Scylla fast magnetic compression experiment.[1,2] The Scylla magnetic field rises sinusoidally to 55 kgauss in 1.25 μsec and produces a deuterium plasma with an ion density of 5×10^{16}/cm^3 which emits neutrons and soft x rays for about 0.8 μsec near the maximum of the second half-cycle of the magnetic field.

The diffracting element of the spectrometer is a beryl crystal, ground for reflection from the $10\bar{1}0$ planes ($2d = 15.94$ A), which allows examination of the plasma emission spectrum between 5 A and 15 A. The energy resolution of the spectrometer is determined by the angular definition of the slit system, which is 10′ of arc for the measurements here reported. The diffracted x rays are recorded by a plastic scintillator–photomultiplier detector, and the time-resolved signal is displayed on an oscilloscope. The detector does not record individual x rays, but rather a pile-up signal whose amplitude indicates the time variation of the intensity of diffracted x rays produced during the 0.8-μsec emission interval at maximum plasma compression.

The line spectra emitted by the deuterium discharge are shown in Fig. 1. The hydrogen-like spectrum of O^{VIII} and the helium-like spectra of Na^{X}, Mg^{XI}, Al^{XII}, and Si^{XIII} are well de-

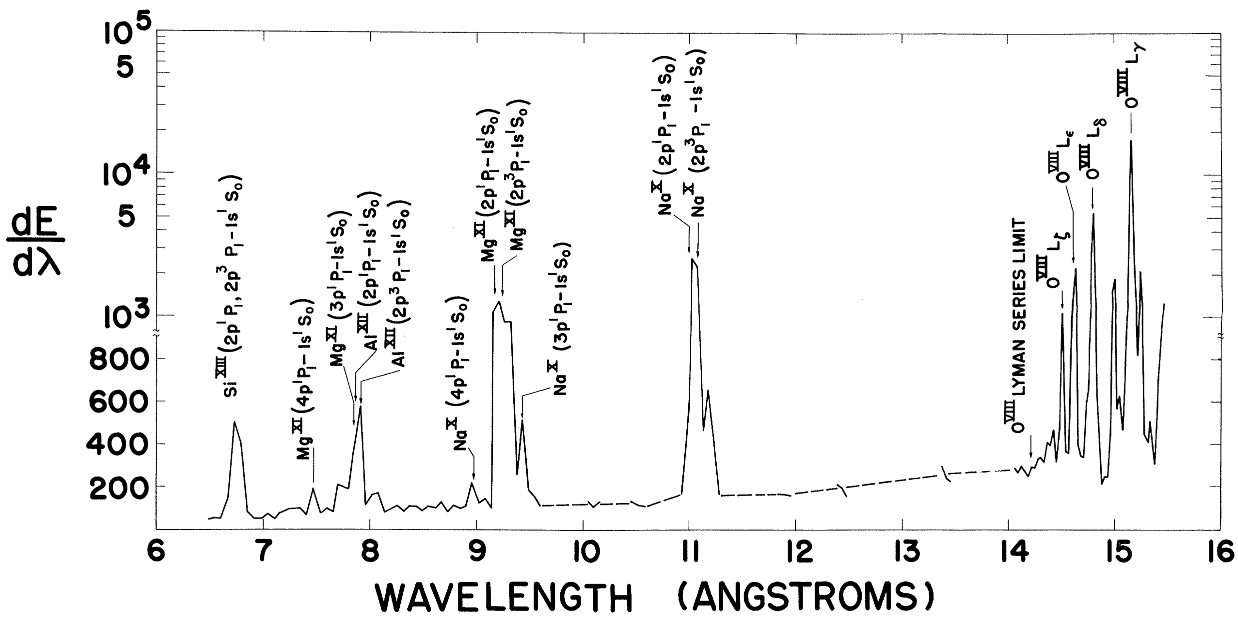

FIG. 1. Spectrum of the deuterium discharge in Scylla. The arrows indicating the identified lines are at the predicted wavelength for each line.

veloped. The most energetic line observed is the Si^{XIII} line corresponding to an excitation of 1.84 kev. The impurities arise from the discharge tube wall which is 96% Al_2O_3 and 4% oxides of Si, Mg, Na, etc. Linear Stark broadening in the Inglis-Teller theory of the merging of the levels at high quantum numbers[3] is too small to account for the observed loss of O^{VIII} Lyman lines at the eighth. It is more likely that the loss results from a combination of merging of the lines by Doppler broadening and instrumental resolution and decreasing intensity of emission at large quantum numbers. An interpretation of the relative intensities of the impurity lines from different elements is complicated by considerations of the relative refractoriness of the constituent wall oxides, and hence the percentage constitution of the impurities in the discharge, and by the fact that the duration of the discharge is too short to produce steady state populations of the ionic species.

The line spectrum produced by the discharge when 10% Ne is added to the deuterium gas is shown in Fig. 2. These lines have not been recorded previously, but their identification is certain since the wavelengths of the observed lines of the helium-like series can be predicted accurately by interpolation from other elements in the isoelectronic sequence.[4] The time-resolved x-ray detector, together with the pulsed Scylla source, provide a powerful technique for identifying the Ne species observed. The satellite lines labeled Ne^{VIII} peak earlier in time during the magnetic compression than the Ne^{IX} lines and are due to screened transitions of K-shell electrons in the more readily produced three-electron species.[5] The weak lines in the hydrogen-like spectrum, Ne^{X} L_α and Ne^{X} L_β, appear later than the Ne^{IX} lines. The intercombination line, $1s\,^1S_0$-$2p\,^3P_1$, is nearly as strong as the corresponding line in the singlet series, as has been discussed by Edlén.[4] The line at 13.66 A is

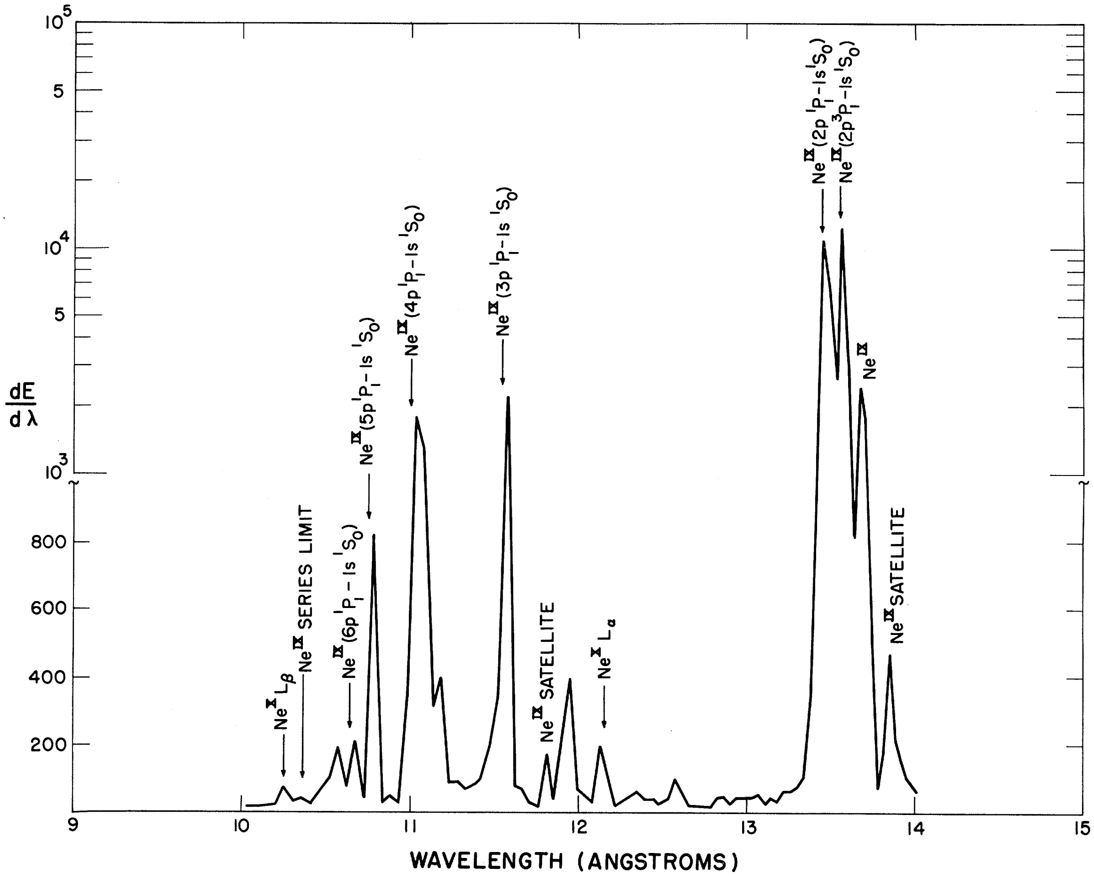

FIG. 2. Spectrum of the Scylla discharge with 10% Ne added to the deuterium gas. The arrows are at the predicted wavelength for each of the identified lines. The probable origin of Ne lines shown without term designations is discussed in the text.

due to Ne^{IX}, since it shows the same time history as the other Ne^{IX} lines. The most plausible assignment is $1s\,^1S_0$-$2s\,^3S_1$, where the normal selection rules are violated because of the strong ionic field.

The spectral energy distribution of the continuum during the second half-cycle is plotted in Fig. 3. Regions of the spectrum containing lines are omitted from this graph. Assuming that the electron energy spectrum is characterized by a temperature T_e and that the continuum consists of free-bound and free-free radiation, a plot of $\ln(dE/d\nu)$ vs ν should be a straight line of slope $-h/kT_e$, except for small quantum-mechanical, Gaunt factor[6] corrections (less than 10% in the frequency interval considered here) and possible discontinuities at the free-bound continuum limits of the various impurity ions. Changes in continuum intensity at the free-bound limits of O^{VIII}, Na^{X}, and Mg^{XI} are not observed, probably because the merging of the broadened spectral lines near each series limit obscures the change in intensity at its edge. The slope of the continuum in the case of a deuterium discharge with no added impurity corresponds to an electron temperature of 345 ± 40 ev; the temperature for a deuterium discharge with 6% oxygen added is 295 ± 30 ev. The greatest uncertainty in the temperature determination lies in the experimental measurements of the beryl crystal reflectivity as a function of wavelength. A previous analysis of the continuum spectrum by absorption methods indicated a somewhat lower electron temperature (240 ev).[2] This is because the newly discovered line radiation distorted the pure free-bound continuum below 14 A assumed for the previous temperature determination.

A detailed description of these and related observations is being prepared for publication in The Physical Review.

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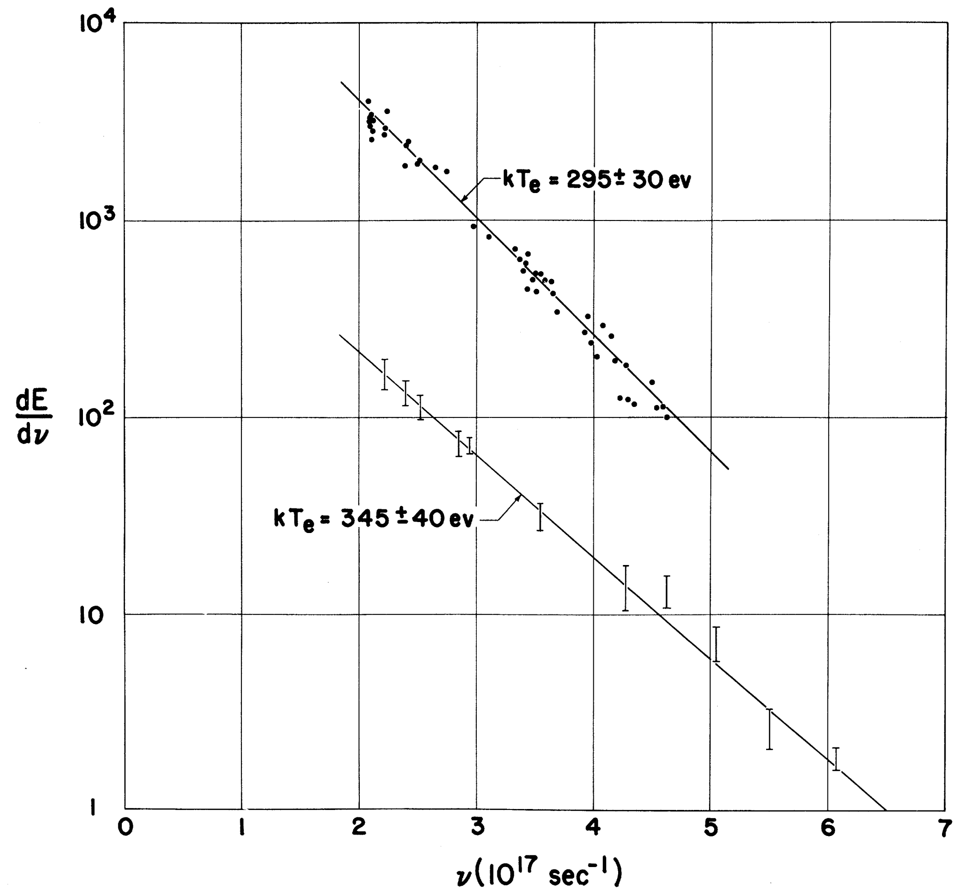

FIG. 3. The continuum spectrum of Scylla. Energy per unit frequency interval is plotted against frequency. Regions of the spectrum containing lines are omitted. The lower curve is for the case of pure deuterium gas and the upper curve for 6% O_2 added to the deuterium. The lines drawn through the experimental points are theoretical slopes for free-free and free-bound radiation at the indicated electron temperatures.

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COSMIC-RAY FLARE OF NOVEMBER 20, 1960

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In recent Letters to this journal, a solar flare, conjectured to have occurred 30° behind the sun's west limb, was credited with production of a cosmic-ray neutron increase[1] and a major 2800-Mc/sec solar noise burst.[2] We believe that at least the elevated portions of this flare, as well as associated prominences, were observed by us.[3] It is well known that flares are not restricted to the chromosphere, but typically occur elevated some thousands of kilometers above the chromosphere.[4-6] Based in the chromosphere 30° beyond the sun's limb, this flare would appear if its radial height exceeded 93 000 km. While certainly rare, flares of comparably great heights have been reported in the literature.[7,8]

The event first appeared at 1955 U.T. as a small mound on the limb of the sun and underwent a gradual increase in area and brightness until 2022 U.T. (see Fig. 1). The maximum brightness occurred between 2017 U.T. and 2024 U.T., and it was only during this period that Lockheed and Sacramento Peak Observatories considered the event to be of flare brightness.

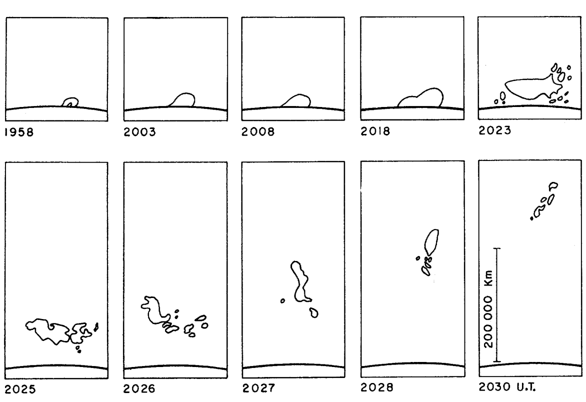

FIG. 1. The solar limb flare of November 20, 1960. West limb, 25° North. High Altitude Observatory, Climax, Colorado.

Abruptly at 2022 U.T. the feature began to ascend, becoming detached from the limb by 2023 U.T., and by 2032 U.T. appeared to have completely disintegrated at a height of 300 000 km above the sun. The transverse velocity was approximately 900 km/sec. Because of the band pass of our filter, material having line-of-sight velocities in excess of about 100 km/sec would not have been observed. Another feature of flare brightness (described by the observer, Keith Watson, as a set of stationary, brilliant, coronal loops) appeared in the region at 2117 U.T. and continued until the end of Climax's observations at 2257 U.T.

The sequence of November 20, 1960 solar and associated events is given in the top of Table I. The following points seem most noteworthy:

(a) The 2800-Mc/sec radio noise burst began with the start of the flare's ascent (2022-2023 U.T.) and continued long after the optical flare disappeared.

(b) The ionospheric effects began between 2023-2028 U.T. and also continued long after the visible flare.

(c) The cosmic-ray increase began at 2055 U.T. (± 10 min), delayed about 33 minutes after the start of the disintegration.

A strikingly similar sequence was also noted for another solar limb flare, believed to be the source of the May 4, 1960 cosmic-ray increase.[9-11] Some of the relevant observations are tabulated in the lower part of Table I. Kleczek and Křivský reported a bright loop expanding with high transverse velocities (plus line-of-sight components of + 170 km/sec to - 90 km/sec) at 1016 U.T. This was followed by the formation of intensely bright coronal loop prominences at 1040 U.T. Such prominences show the existence of regions of high density and strong, ordered magnetic fields in the sun's corona, ingredients which are likely