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The ALS—A Third-Generation Light Source

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The Advanced Light Source, a third-generation national synchrotron-radiation facility now under construction at the Lawrence Berkeley Laboratory, is scheduled to begin serving qualified users across a broad spectrum of research areas in April 1993. Based on a low-emittance electron storage ring optimized to operate at 1.5 GeV, the ALS will have 11 long straight sections available for insertion devices (undulators and wigglers). Undulators will generate high-brightness soft x-ray and ultraviolet (XUV) radiation; wigglers will extend the spectrum generated into the hard x-ray region, but at a lower brightness. Up to 48 bending-magnet ports will also be available.

Engineering design has begun on a complement of three undulators with periods of 8.0, 5.0, and 3.9 cm that between them will cover the photon-energy range from 5.4 eV to 2.5 keV when the first, third, and fifth harmonics are used, as well as a wiggler with a critical energy of 3.1 keV. Undulator beam lines will be based on high-resolution spherical-grating monochromators.

A Call for Proposals has been issued for those who wish to participate in the design, development, commissioning, and operation of the initial complement of ALS experimental facilities (insertion devices, beam lines, and experimental stations) as members of a participating research team. The deadline for receipt of proposals was August 15, 1989. Proposals are expected to reflect the Letters of Interest received from potential PRTs during the previous year.

I. INTRODUCTION

The availability of intense, tunable, collimated, polarized radiation in the x-ray and ultraviolet (collectively, the XUV) regions of the spectrum has driven the evolutionary development of dedicated facilities optimized for the generation of synchrotron radiation [1]. The newest, third-generation synchrotron sources are based on the use of an electron or positron storage ring specifically designed to have a very low emittance and several long straight sections containing insertion devices (wigglers and undulators).

The combination of a very-low-emittance storage ring with optimized undulators makes possible the generation of radiation with a spectral brightness (sometimes also called brilliance) that is increased by a factor of 20 or more over that of existing, second-generation sources, depending on the spectral range. In the past, order-of-magnitude increases in brightness have led to qualitatively new developments in spectroscopic and structural studies of both gas-phase and condensed matter. The increased brightness of the third-generation synchrotron sources is expected to have a similar effect [2,3].

Around the world, construction of several third-generation synchrotron sources is either under way or planned, including the Advanced Light Source (ALS) at the Lawrence Berkeley Laboratory. The ALS is in its third year as a U.S. Department of Energy-funded construction project with a total estimated cost (TEC) of $99.5 million. The project is scheduled to be completed in April 1993.

II. STORAGE-RING OVERVIEW

The ALS will be housed in an expanded version of the domed hall that once was the home of the historic 184-Inch Synchrocyclotron at the Lawrence Berkeley Laboratory. An overall layout of the facility's accelerator complex, which consists of a 50-MeV linac, a 1-Hz, 1.5-GeV booster synchrotron, and an electron storage ring, is shown in Fig. 1. Although the energy range of the storage ring will be from 1 to 1.9 GeV, its performance is optimized at 1.5 GeV.

Performance characteristics of the ALS are determined primarily by the design of the storage-ring magnet lattice—the arrangement of bending and focusing magnets in the ring. For the ALS, the lattice has 12 long straight sections that are joined by 12 achromatic arcs, each containing three bending magnets. This structure is referred to as a triple-bend achromat (TBA). Each of the 12 identical segments (superperiods) of the ALS lattice also contains six quadrupole focusing magnets and four sextupole magnets.

The ALS produces electron beams that are bunched rather than continuous. The storage-ring rf system has a frequency of 500 MHz, so that the spatial separation between bunches is 0.6 m and the temporal separation is 2 ns. The storage-ring lattice, the rf system, and the impedance of the vacuum-chamber hardware determine the length (spatial and temporal) of the bunches. For the ALS at the nominal current of 400 mA, the predicted full-width-at-half-maximum value of the bunch length is 35 ps.

To avoid trapping positive ions in the potential well of the negatively charged electron beam, the multibunch mode with a 400-mA current will have 250 contiguous bunches, followed by a gap of 78 empty buckets . For particular experiments—for example, those involving time-of-flight measurements—it can be advantageous to have only one or a few circulating electron bunches in the storage ring. In the few-bunch mode, the nominal per bunch will be 7.6 mA and the bunch length (FWHM) is predicted to be 55 ps, although still larger bunch currents may be tolerated (with additional bunch lengthening) before the beam becomes unstable.

The ALS is described in detail in a conceptual design report [4]. All the performance data reported here are from An ALS Handbook [5]. A summary of the major parameters of the storage ring is given in Table 1.

III. PHOTON SOURCES

The ALS lattice is optimized for the use of insertion devices. The periodic magnetic field of an insertion device bends the electrons into an approximately sinusoidal trajectory in the horizontal plane, causing the emission of synchrotron radiation . Of the 12 straight sections in the storage ring, one is used for injection and one is partially occupied by rf cavities, leaving 10 full straight sections available for undulators and wigglers up to 5 m in length. One partial straight section will be also available. Operating at 1.5 GeV, the ALS is optimum for insertion-device operation in the XUV spectral regions. Table 2 lists the properties of a complement of three undulators that span the soft x-ray and ultraviolet spectral regions when the ALS operates at 1.5 GeV and a wiggler that extends spectral coverage into the hard x-ray region.beyond 10 keV

The spatial pattern of undulator radiation is a complex pattern of rings, but on the axis of an undulator, the spectrum of radiation consists of a series of narrow peaks, a fundamental and its harmonics

$$\varepsilon_n[\text{keV}] = 0.950\, nE^2[\text{GeV}]/(1 + K^2/2)\lambda_u[\text{cm}],$$

where ε_n is the photon energy of the nth harmonic, E is the photon energy, K is the deflection parameter, which is proportional to the undulator magnetic field and is usually about equal to 1, and λ_u is the period of the undulator [4,5]. The relative bandwidth of each peak is approximately

$$\Delta\varepsilon/\varepsilon = 1/nN,$$

where N is the number of periods. In general, the spectral brightness of undulator radiation is also proportional to N^x where x is between 1 and 2.

The spectral range of the undulator is scanned by varying the undulator magnetic field, which decreases as the gap between the poles of the undulator increases. Scanning from low to high photon energies is therefore accomplished by moving the gap from a minimum to a maximum distance, both arbitrarily set by the drop off of the photon flux at low and high gap values but also subject to constraints such as the vertical diameter of the storage ring vacuum chamber. At the ALS, it is planned to use the third and fifth harmonics of the undulators to extend their spectral range to higher photon energies than can be reached with the fundamental alone. Between them, the three undulators will cover the spectral range from 5.4 eV to 2.5 keV.

The wiggler, which operates with a high magnetic field and hence a K value much greater than 1, generates broad continuous spectrum characterized by a critical photon energy ε_c, defined as the photon energy above and below which half the total power is radiated. At the high end of the broad wiggler spectrum, the flux drops rapidly but is still one-tenth of its maximum value at photon energies near 4 ε_c. With an ε_c of 3.1 keV, the ALS spectral range extends into the hard x-ray region near 10 keV, although the increased spectral range comes at the expense of a reduced brightness.

Synchrotron radiation will be available from the bending magnets, as well as from the insertion devices. The critical photon energy of the bending magnets is 1.56 keV. Because the center bending magnet in each arc can accommodate two ports, up to four bending-magnet ports per superperiod of the storage-ring would be available, making a total of 48 ports for the entire ring. The locations of the insertion-device port and the four bending-magnet ports in one superperiod of the storage-ring lattice are shown in Fig. 2.

The spectral brightness as a function of photon energy are shown in Fig. 3 for the three undulators and one wiggler described in Table 2, together with the ALS bending magnets. The spectral brightness as a function of photon energy is shown in more detail in Fig 4 for the fundamental and for the third and fifth harmonics of the undulators. In general, there can be many prominent higher harmonics, especially for undulators operating at K values much greater than 1.

Based on the user requirements expressed in several topical workshops and in letters of interest received from prospective participating research teams, conceptual design studies have begun on these insertion devices and on beam lines to carry the XUV radiation to experimental areas. The philosophy for the initial complement of insertion devices is to create a generic design and thereby reduce engineering and fabrication costs and enhance maintainability. The goals of very high brightness and useful fifth-harmonic output impose unusually tight tolerances on the magnetic-field quality and thus on the mechanical structure of the undulator.

IV. INSERTION-DEVICE BEAM LINES

Advances in storage-ring technology and the development of insertion devices have created new challenges for optical designers, especially in two areas:

- The source size has become smaller, so that relay optics require tighter tolerances to avoid loss of light. The use of smaller slits also becomes practical so that monochromator components need tighter tolerances in both optical figure and finish to avoid loss of resolution.

- The photon-beam power has increased to the point that optical components must be cooled to control thermal distortions and stress, thereby complicating the design and limiting the choice of materials.

To meet these challenges, it is planned to base the undulator beam lines on the Rense and Violett spherical-grating monochromator system [5]. According to the scheme published by W.A. Rense and T. Violett in 1959 [6], the astigmatism associated with spherical gratings can be corrected by a condensing system that images the source onto the entrance slit in the dispersion (vertical) plane and onto the exit slit in the horizontal plane. Although wave-length tuning is by simple rotation of the grating, either the entrance or the exit slit (or both) must be movable to keep them near (or on) the Rowland circle during wavelength scanning.

The condensing system chosen for ALS undulator beamlines consists of two spherical mirrors with their planes of incidence perpendicular to each other in the configuration originated by Kirkpatrick and Baez in 1948. Each mirror has nearly zero focusing effect in its sagittal direction. Because of the low emittance of the ALS storage ring, the monochromator can accept the entire undulator beam in most cases, even at a slit-width of 10 μm. Individual variations in details, such as the elimination of one or both of the condensing mirrors, are also being investigated for the ALS.

V. CALL FOR PRT PROPOSALS

Letters were mailed in March 1989 to those on the ALS mail list, and advertisements appeared in the April issues of several scientific publications serving the synchrotron-radiation community, all to announce a Call for Proposals from Participating Research Teams (PRTs) to develop and operate the initial complement of beam lines and experimental facilities at the ALS. The deadline for receipt of proposals was August 15, 1989.

Proposals were invited from PRTs to work with the ALS staff on the design, construction, and commissioning of insertion devices and beam lines, to develop the associated experimental apparatus, and to carry out the initial scientific program with these facilities. Proposals were especially encouraged from insertion-device teams, with proposals from bending-magnet teams to be considered to the extent that resources permit.

Privileged access to the facilities it helps develop will be assigned to each PRT for its own research program, with the amount of access dependent on the resources (personnel, funding, and equipment) provided for the facilities by the PRT. The remaining access will be available to general users. There will be a call at a future date for proposals from general users desiring to use these facilities.

To stimulate the formation of prospective participating research teams and to gauge their requirements for experimental facilities, during the spring of 1988, a Call for Letters of Interest was issued. It is expected that the response to the Call for Proposals will reflect the letters of interest received during the last year, as summarized in Table 3. The areas of research covered include:

-- materials science of interfaces,
-- materials science of solids and buried interfaces,
-- spatially resolved microscopy (spectromicroscopy) of materials and surfaces,
-- spectroscopy of the actinide elements,
-- time-resolved spectroscopy of solids and surfaces,
-- infrared surface science,
-- microscopy and coherent optics for the physical sciences,
-- microscopy and spectroscopy of mineral surfaces,
-- spatially resolved elemental analysis of rocks and minerals,
-- molecular dynamics with laser/synchrotron-radiation techniques,
-- gas-phase photoprocesses in atoms and molecules, (12) gas-phase molecular spectroscopy,
-- x-ray microscopy for the life sciences,
-- x-ray crystallography of biological macromolecules,
-- spectroscopy for the life sciences,
-- circular dichroism of biological material,
-- radiobiology,
-- time-resolved studies of biomolecules.

Reviewing of proposals for the first beamlines will begin before the end of 1989. Two advisory panels, a seven-person Science Policy Board and a nine-person Program Review Panel, with complementary functions, have been established and charters outlining the composition and duties of these bodies have been approved by the Laboratory management. According to these charters, the Science Policy Board "is appointed by the LBL Director to provide advice on major policy issues that bear on effective utilization of the ALS," while the Program Review Panel "is advisory to the LBL Director and will provide him, through the ALS Director, with specific recommendations on the disposition of all proposals for the development and use of beamlines of all types." Tables 4 and 5 give the compositions of these bodies.

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[2] Report of the Workshop on an Advanced Soft X-Ray and Ultraviolet Synchrotron Source, PUB-5154 (Lawrence Berkeley Laboratory, Berkeley, CA, 1985).
[3] Proc. 1st Users Meeting for the Advanced Photon Source, ANL/APS-CP-1 (Argonne National Laboratory, Argonne, IL, 1988).
[4] 1-2 GeV Synchrotron Radiation Source, PUB-5172 Rev. (Lawrence Berkeley Laboratory, Berkeley, CA, 1986). Note that the values of some ALS parameters have changed since the issuance of this report.
[5] An ALS Handbook, PUB-643 Rev. 2 (Lawrence Berkeley Laboratory, Berkeley, CA 1989).
[6] W. A. Rense and T. Violett, J. Opt. Soc. Am. 49 (1959) 139.

Table 1. Main Parameters of ALS Storage Ring

Beam energy [GeV]	
Nominal	1.5
Minimum	1.0
Maximum	1.9
Circumference [m]	196.8
Beam current [mA]	
Multibunch	400
Single bunch	7.6
Beam emittance, rms [nm·rad]	
Horizontal	10
Vertical	1
Relative rms momentum spread	
Multibunch	8.0 x 10-4
Single bunch	13.0 x 10-4
Nominal bunch duration, FWHM [ps]	30-50
Radiation loss per turn [keV]	92
Length available for insertion devices [m]	5

Table 2. Parameters for a Possible Initial Complement of ALS Insertion Devices

Name	Period (cm)	No. of periods	Photon Energy range (eV)[a]	Critical energy (keV)
Undulators				
U8.0	8.0	61	5.4–220[b] [16.2–660] [27–1100]	–
U5.0	5.0	98	52–380 [156–1140] [260–1900]	–
U3.9	3.9	123	169–500 [507–1500] [845–2500]	–
Wiggler				
W13.6	13.6	16	–	3.1

[a]The photon energy range of the fundamental and of the third and fifth harmonics (shown in brackets) as the deflection parameter K decreases from its maximum value to approximately 0.5, when the electron-beam energy is 1.5 GeV.

[b]Below about 8 eV in the fundamental, the peak field in undulator U8.0 exceeds the bending-magnet field and may affect storage-ring operation.

Table 3. ALS Letter of Interest Summary

NUMBER OF INSTITUTIONS	53
Academic	39
Government Lab.	10
Industry	4
NUMBER OF INDVIDUALS	164
Academic	66
Government Lab.	74
Industry	24
LETTERS OF INTEREST BY FIELD[a]	
Materials, Interfaces, and Surfaces	8.5
Atoms, Molecules, and Chemistry	5
Life Sciences	6.5
Geosciences	2

[a]Total of 22 excludes five letters of interest for bending-magnet teams in association with insertion-device teams.

Table 4. Members Advanced Light Source Program Review Panel

Chair: Dr. Neville V. Smith AT&T Bell Laboratories	Prof. Giorgio Margaritondo University of Wisconsin
Dr. C. Richard Brundle IBM Almaden Research Center	Prof. Keith Moffat Cornell University
Dr. Sheldon Datz Oak Ridge National Laboratory	Prof. J. Michael White University of Texas at Austin
Dr. Michael L. Knotek, Pacific Northwest Laboratory	Dr. Joe Wong Lawrence Livermore National Laboratory
Prof. Robert I. Macey University of California at Berkeley	

Table 5. Members Advanced Light Source Science Policy Board

Chair: Dr. Albert Narath Sandia National Laboratories	Prof. Bernd Crasemann University of Oregon
Prof. Richard Bernstein University of California at Los Angeles	Dr. Dean E. Eastman IBM T.J.Watson Research Center Los Angeles
Prof. E. Morton Bradbury University of California at Davis	Prof. Herbert H. Johnson Cornell University
Dr. John C. Browne Los Alamos National Laboratory	Dr. J. M. Paterson Stanford Linear Accelerator Center

FIGURE CAPTIONS

Fig. 1. Layout of the ALS accelerator complex showing the placement of the 50-MeV electron linear accelerator, the 1.5-GeV booster synchrotron, and the storage ring.

Fig. 2. Arrangement of photon-beam ports in one superperiod of the storage-ring lattice showing one insertion-device port and four bending-magnet ports.

Fig. 3. Spectral brightness as a function of photon energy for the three undulators and one wiggler described in Table 2, together with the ALS bending magnets. Each undulator curve is the locus of narrow peaks of radiation, tuned by altering the undulator gaps, and represents the envelope of the first, third, and fifth harmonics.

Fig. 4. Spectral brightness as a function of photon energy in more detail for the three undulators described in Table 2. Each undulator curve is the locus of narrow peaks of radiation, tuned by altering the undulator gap. Separate curves are shown for the first, third, and fifth harmonics of each undulator. The dotted extension of the first harmonic of U8.0 represents the performance when the undulator field exceeds the bending-magnet field, a condition that may affect storage-ring operation.

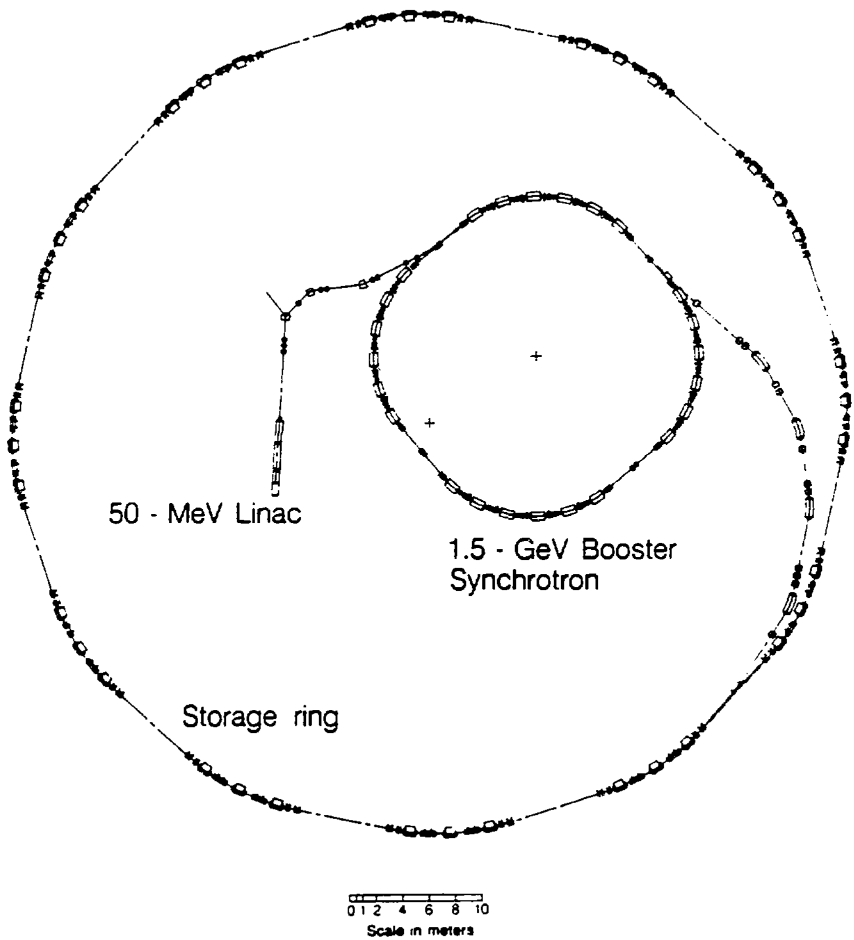

FIG. 1

XBL 893-7086

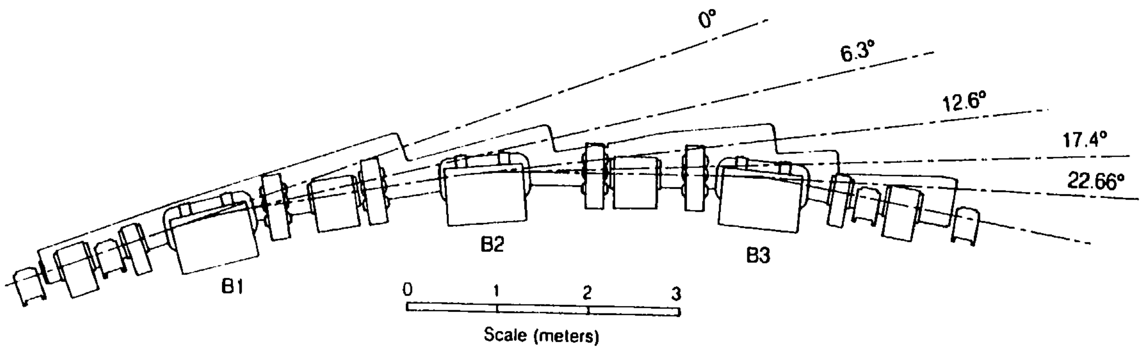

FIG. 2

XBL 893-7092

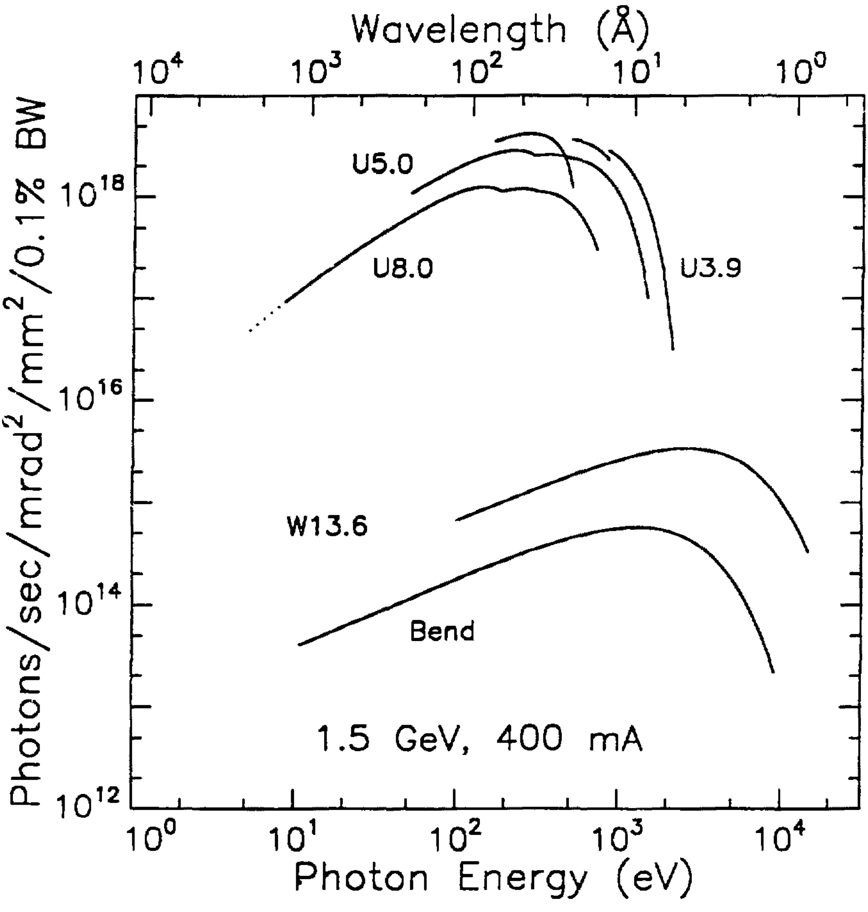

FIG. 3

XBL 893-7100

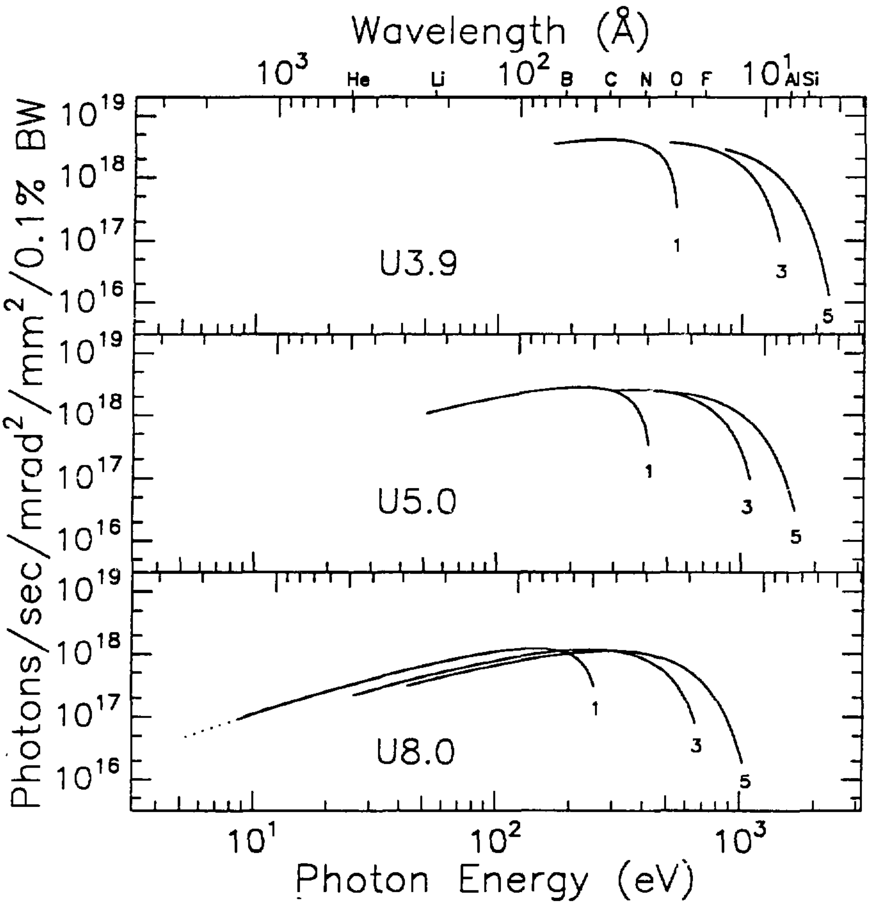

FIG. 4

XBL 893-7096