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WHITE PAPER ON SBUV/2 SOLAR IRRADIANCE MEASUREMENTS

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1. EXECUTIVE SUMMARY

The primary goal of the Solar Backscatter Ultraviolet, Model 2 (SBUV/2) instruments on NOAA's operational satellites is to accurately monitor long-term changes in the global column ozone amount and the altitude distribution of ozone in the upper stratosphere. A related, important goal is to provide researchers with the fundamental data needed to separate anthropogenic ozone change from natural ozone change. The purpose of this *White Paper On SBUV/2 Solar Irradiance Measurements* is to describe the importance of the SBUV/2 solar irradiance measurements, which are necessary to meet these goals.

Needed to accomplish the primary goal are:

- weekly solar irradiance measurements at the operational ozone wavelengths
- daily measurements of the Mg II proxy index
- instrument-specific Mg II scale factors

Needed to accomplish the second goal are:

- daily measurements of the solar spectral irradiance at photochemically important wavelengths

The SBUV/2 instruments on the NOAA-9, NOAA-11, and NOAA-14 satellites have made daily solar irradiance measurements since March 1985 in support of their operational ozone measurements. Solar measurements at the operational ozone wavelengths (252-340 nm) are used to accurately determine the terrestrial geometric albedo, which is inverted to derive the column ozone amount and its altitude distribution. It is now known that solar-induced ozone change is comparable in magnitude to anthropogenic ozone change. Hence, solar monitoring at the wavelengths important to ozone photochemistry (200-300 nm) is a vital component of the long-term ozone monitoring program.

Direct measurements of solar UV variations are hindered by the formidable task of accurately maintaining instrument calibrations to better than 1% over a solar cycle. To date, no experiment team (including either of the two UARS solar instrument teams) has met this goal. In response to this problem, the Mg II proxy index was designed to accurately track solar variations. The SBUV/2 Mg II index products and associated solar variability scale factors are used by over two dozen scientists from seven countries to monitor solar change at photochemically important wavelengths. For this reason, and for direct use in calculating the terrestrial geometric albedo, daily Mg II measurements and spectral scan measurements needed to determine the instrument-specific scale factors are required.

This *White Paper* provides recommended instrument solar measurement schedules for NOAA's SBUV/2 instruments. Two schedules are provided: 1) a baseline schedule for all instruments expect the NOAA-14 instrument, and 2) a modified schedule for the NOAA-14 SBUV/2 instrument. This latter schedule is needed due to the NOAA-14 grating drive problems. This *White Paper* concludes with a detailed scientific justification for the recommended measurements.

2. RECOMMENDED SBUV/2 INSTRUMENT SOLAR MEASUREMENT SCHEDULES

2.1 Baseline Schedule

The recommended baseline schedule of solar observations from future SBUV/2 instruments is identical to the schedule which has been used since early 1985 for operations on the NOAA-9 and NOAA-11 SBUV/2 instruments:

1) Weekly discrete mode solar irradiance measurements at the wavelengths used for operational ozone monitoring.

2) Daily discrete mode solar irradiance measurements at the Mg II wavelengths.

3) Daily sweep mode solar irradiance measurements.

2.2 NOAA-14 SBUV/2 Schedule

Daily NOAA-14 sweep mode solar irradiance operations were discontinued on 7 October 1995 due to the "sticking" of the grating drive mechanism in the sweep mode. Daily discrete mode solar irradiance measurements at a set of wavelengths selected to maximize solar variability monitoring are recommended as a replacement of the daily sweep mode solar operations for the NOAA-14 SBUV/2 instrument. The rationale and details of these measurements are discussed in Sections 3.2 and 4, respectively. Daily NOAA-14 discrete mode Mg II measurements commenced on 30 January 1996. Unfortunately, the Mg II doublet location corresponds to the portion of the NOAA-14 grating drive that experiences the most severe problems, and to date no NOAA-14 discrete mode Mg II data have been successfully acquired. As discussed in Section 4, an alternate set of discrete mode Mg II wavelengths is recommended for this instrument. The recommended solar observation schedule for the NOAA-14 SBUV/2 instrument is thus:

1) Weekly discrete mode solar irradiance measurements at the wavelengths used for operational ozone monitoring. Commencing 2 January 1996 these are the standard "zig zag" wavelengths.

2) Daily discrete mode solar irradiance measurements at a revised set of Mg II wavelengths. (Note that these measurements may be discontinued if grating sticking problems continue even at the alternative Mg II wavelengths).

3) Daily discrete mode solar irradiance measurements at the set of wavelengths used as a replacement for the sweep mode measurements.

The recommended wavelengths and grating positions for NOAA-14 SBUV/2 instrument operations are listed in Table 1.

3. SCIENTIFIC JUSTIFICATION

There are two motivations for measuring the solar spectral irradiance on a daily basis from the SBUV/2 instruments on NOAA's TIROS operational satellites:

1) Need to account for the direct impact of solar irradiance change on the SBUV/2-measured terrestrial geometrical albedos and hence on the retrieved total column ozone and profile ozone.

2) Need to assess the short, medium, and long-term ozone response to solar variations.

Each motivation is discussed in turn.

3.1 Accurate Retrieval of Total Column Ozone and Ozone Profile

The fundamental quantity used to derive ozone in the backscattered ultraviolet (BUV) technique is the terrestrial albedo, α_λ, which is the ratio of the radiance backscattered from the earth-atmosphere system (I_λ) to the incident solar irradiance (F_λ):

$$\alpha_\lambda = I_\lambda / F_\lambda$$

The backscattered radiance is proportional to the incident solar irradiance multiplied by the bidirectional reflectance distribution function (BRDF) of the earth-atmosphere system (the BRDF contains all the physics of the radiative transfer - Rayleigh and aerosol scattering, ozone absorption, etc.). Variations in the incident solar flux, which occur due to changes in the sun-earth distance and due to changes in the sun's output, lead to direct, proportional changes in the backscattered radiance. Knowledge of the time variations of solar irradiance at the operational ozone wavelengths is thus required for accurate retrieval of the total column ozone amount and its altitude distribution from NOAA's SBUV/2 instruments.

The radiance and irradiance measurements are ideally made at the same time so that both solar change and any instrument sensitivity drift cancel out in the albedo. This is unwieldy to do in practice. Operationally, SBUV/2 discrete mode solar irradiance measurements are performed once per week. Thus, any shorter-term solar change is not completely sampled, possibly giving rise to errors in the measured albedo and hence the retrieved ozone. How significant is this effect?

Middle UV solar variations have been studied by many researchers, including (to cite only a few) Donnelly et al. (1986), Heath and Schlesinger (1986), Labs et al.(1987), Donnelly (1988), Schlesinger and Heath, (1988), Cebula et al. (1991), Lean et al., (1992), DeLand and Cebula (1993), and London et al. (1993). These scientists have shown that short-term middle UV solar variations can be modeled using the Mg II proxy index and scale factors, shown in Figures 1 and 2, respectively.[1] Near solar maximum, solar rotational variations, as measured using the SBUV/2 Mg II index, can be as large as 6-8%. The amplitude of the solar rotational variations diminishes as solar activity decreases, and near solar minimum rotational variations are typically only 1-2%. The scale factors relate the solar change at a given wavelength to the Mg II index; a scale factor of unity (1.0) means that for that wavelength a 1% change in the Mg II index corresponds to a 1% change in the wavelength's solar irradiance. The scale factors at the wavelengths used by the SBUV/2 instruments for ozone measurement range from approximately 0.48 at 252 nm, to 0.14 at 274 nm, 0.11 or less between 283 nm and 306 nm, and less than 0.01 for the total ozone wavelengths ($\lambda \geq 312$ nm). Thus, at solar maximum conditions, solar rotational irradiance variations can be as large as roughly 3.4% at 252 nm, 1% at 274 nm, 0.7% at 283 nm, and less than 0.1% at the total ozone wavelengths. The period of the rotational variations is typically approximately 27 days (although the exact period is quite variable, and strong 13.5 day periodicity is also observed during solar maximum). Given once per week sampling, it is possible to underestimate the amplitude of solar rotational variations by a factor of approximately 1/3.

Considering solar maximum conditions, at 252 nm the SBUV/2 instruments' once per week sampling can translate into roughly a 1% error in the measured amplitude of the solar rotational change. The calculated 252 nm albedo would thus also be in error by 1%. The effect of this error on derived ozone depends on the ozone amount and solar zenith angle, but, for a typical mid-latitude ozone amount, would give rise to an approximate 1.9% error in the 1 mbar ozone retrieval (Fleig et al., 1990). The potential error in the retrievals decreases with decreasing altitude because 1) there is less solar variation at the longer wavelengths (whose contribution functions peak lower in the atmosphere than does the 252 nm contribution function), and 2) the sensitivity of the retrieved ozone to a given change in albedo decreases at the longer wavelengths.

A second problem is that, given once per week sampling, it is possible to introduce a 1-2 day phase error between the apparent extrema of the solar rotational cycle and the actual location of the extrema. This error gives rise to erroneous phase relations in studies of the influence of short-term solar variations on upper stratospheric ozone (Chandra et al., 1994).

Thus, near solar maximum, the once per week measurement of the solar irradiance can give rise to errors as large as approximately 2% in the derived 1 mbar ozone. Studies of the short-term response of upper stratospheric ozone to solar variations would thus be in error.[2] Previously, these problems were overcome by using the Mg II proxy index and scale factors to account for the short term solar change during the derivation of the SBUV/2 Albedo Correction Factors (ACF; used to correct the

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[1]The Mg II proxy index and scale factors are also used to bypass the effects of instrument sensitivity drift, which can impact direct solar irradiance measurements.

[2]It is for these reasons that the operational ozone product, where the Albedo Correction Factors are based on the weekly solar irradiance measurements, cannot be used to study the response of stratospheric ozone to short-term solar variations. The reprocessed product, wherein the Mg II index is used to properly account for solar rotational variability, can be used to study the response of ozone to solar rotational change.

measured albedo for instrument drift and solar change). Traditionally, the Mg II proxy index used in the process was based on the daily SBUV/2 sweep mode measurements. Recent work indicates that a Mg II proxy index based on the daily SBUV/2 discrete mode solar Mg II data is more precise and even less sensitive to instrument drift than is the Mg II index constructed using sweep mode data (DeLand and Cebula, 1994).

Hence, if discrete mode Mg II data are taken from a given SBUV/2 instrument, or if an equivalent data set is available as a substitute (for example, the UARS SUSIM instrument currently provides a Mg II proxy index), then it is no longer critical that the SBUV/2 instrument perform daily sweep mode solar irradiance measurements *during the entire lifetime of the mission*. However, due to differences in instrument bandpass and slit function from one instrument to the next, the scale factors are unique for each instrument (Anderson and Hall, 1989; Cebula et al., 1992; DeLand and Cebula, 1993). For example, the scale factors appropriate for the NOAA-14 SBUV/2 instrument are slightly different from the NOAA-11 SBUV/2 instrument scale factors. Further, the use of a external solar variability proxy (such as the UARS SUSIM Mg II index or the ground based He 1083 nm index) requires the derivation of a new set of scale factors applicable to the proxy. Again, these scale factors are unique for each instrument. It is preferable to derive the scale factors using sweep mode data in order to fully characterize solar spectral variations over the entire wavelength range 160-406 nm. Thus, accurate derivation of the scale factors and hence accurate assessment of solar change requires some period of daily sweep mode solar measurements from each of the SBUV/2-series instruments.

3.2 Evaluation of Solar-Induced Ozone Change

An important aspect of the stratospheric change monitoring program is the determination of the cause of any observed ozone change. Solar radiation in the wavelength region between 200 and 240 nm is primarily responsible for the formation of stratospheric ozone (Brasseur, 1993), and the irradiance at 205 nm is often used as an index to represent the intensity of the solar forcing on the stratosphere. Recent work (Brasseur, 1993; Hood et al., 1993; Chandra and McPeters, 1994) suggests that the change in solar UV flux over a solar cycle gives rise to a 1-2% change in total column ozone and about a 5-7% change in ozone mixing ratio in the upper stratosphere (0.7 to 2 mbar). Because it is primarily driven by dynamics rather than photochemistry, the total column ozone amount has little response to short-term (solar rotational length) solar change. Upper stratospheric ozone change is dominated by photochemistry, and can vary by roughly 4% peak-to-peak in response to solar rotational variation. It is therefore important to monitor both short-term and long-term solar variations in order to understand the contribution of solar change to any observed ozone change.

The near daily sweep mode solar irradiance measurements begun by the Nimbus-7 SBUV instrument in late 1978 and carried on by the NOAA-9, NOAA-11, and NOAA-14 SBUV/2 instruments represent the only solar cycle-length middle UV solar irradiance measurements. While other solar instruments exist at present (the UARS SOLSTICE and SUSIM instruments and the GOME instrument began solar measurements in the 1991 and 1995, respectively), the long-term availability of data from these instruments is questionable. None of these instruments (including the two UARS instruments) has to date demonstrated the ability to monitor long-term changes in the solar spectral irradiance at the wavelengths which are important for ozone photochemistry to within the required 1% accuracy. In the absence of direct measurements of sufficient accuracy, another means is needed to monitor long-term solar UV irradiance variations.

It is well established that measurements of the Mg II proxy index can be used to model the short-term behavior of the 205 nm solar irradiance (Heath and Schlesinger, 1986; Cebula et al., 1992; DeLand et al., 1993; Chandra et al., 1995). While it is not yet proven that the Mg II proxy index can be used to accurately predict the long-term behavior of the 205 nm flux (Lean, 1991), the work of Chandra et al. (1995) and Lean (private communication, 1995) looks promising. At minimum, the Mg II index and scale factors can be used to precisely measure relative solar spectral variations. Over two dozen researchers from the United States, Egypt, France, Greece, Italy, Norway, and Russia have used Mg II index data and scale factors from the SBUV/2 instruments to assess solar change and its influence on the middle atmosphere. A list of recent SBUV/2 Mg II proxy index users is given in Table 2.

Thus, monitoring of the middle UV solar flux at the wavelengths which most influence stratospheric ozone can currently best be performed by the SBUV/2 instruments themselves. Measurements at the Mg II wavelengths are needed. As previously stated, at least some period of sweep mode measurements from each of the SBUV/2 instruments is also necessary to derive the instrument-specific Mg II scale factors. Further, long-term sweep mode measurements are desirable because they furnish daily measurements over the entire spectral region 160 to 405 nm, which is desirable for understanding instrument behavior as well as solar variations (Figure 3). While the SBUV/2 instruments do not have an end-to-end instrument calibration capability, needed to unambiguously directly monitor long term solar variations, work is now underway to use periodic underflights of the SSBUV instrument to maintain the calibrations of the SBUV/2 instruments (Cebula et al., 1994).

4. NOAA-14 SBUV/2 SOLAR OPERATIONS

Given the ongoing problems with the NOAA-14 SBUV/2 instrument's grating drive it is advantageous to take two actions. **First, daily Mg II discrete mode measurements should be continued**. These measurements will extend the operational, daily discrete mode Mg II solar measurements performed by the NOAA-9 and the NOAA-11 SBUV/2 instruments. It is unfortunate that the worst grating sticking problems experienced by the NOAA-14 instrument occur near grating position 140 - essentially in the center of the 280 nm Mg II doublet. Data from the first nine days of NOAA-14 operations at the standard discrete mode Mg II wavelengths show serious sticking problems. This seems to be related to the location of the most significant grating drive problems and the fact that the standard discrete mode Mg II core wavelengths are separated from one another by only two grating positions (hence the grating drive motor generates little torque in stepping from one wavelength to next). An alternate set of Mg II discrete mode wavelengths, Table 1, will maximize the amount of motor torque and may overcome the grating sticking problems for the discrete mode Mg II measurement. It is thus recommended that the NOAA-14 SBUV/2 memory segment holding the standard discrete mode Mg II grating positions be reprogrammed with this alternate set of grating positions. The resulting daily Mg II discrete mode data can be evaluated in near-real time to assess whether or not these measurements are successful and should be continued.

In light of the NOAA-14 SBUV/2 instrument's sweep mode problems and the uncertainty in the accuracy of using the Mg II index as a proxy for long-term solar change near 205 nm, a second proposal is put forth. **In place of the daily sweep mode solar irradiance measurements, daily discrete mode solar observations should be performed using an alternate set of wavelengths** (DeLand, 1995). These wavelengths, listed in Table 1 and identified in Figures 2 and 3, represent the most active absorption (and one emission) lines in the 160 to 405 nm region, as well as other, less variable, wavelengths for reference. Although not providing as much spectral information as the sweep mode measurements (only 12 rather than 1680 wavelengths are sampled), the resulting discrete mode solar data would actually be of higher quality than the sweep mode data because of 1) higher signal-to-noise ratio in the discrete mode relative to the sweep mode, 2) increased number of scans per day (approximately 8-10 in the discrete mode versus 2 in the sweep mode), and 3) better short-term and long-term wavelength stability in the discrete mode versus the sweep mode. No significant changes would be required in the planned NOAA-14 SBUV/2 operations schedule, simply a different set of grating positions would be used in addition to the acquisition of solar data at the ozone and Mg II wavelengths. Further, these measurements would have no impact on the operational ozone data.

Previous research has established that each solar cycle is unique (Lean, 1991), thus one cannot extrapolate solar irradiance changes from one solar cycle to the next. Long-term monitoring of the solar spectral irradiance is thus desired, not only for its direct implications regarding global climate change and understanding the photochemical response of ozone and other trace gases to solar forcing, but also to monitor and understand short and long-term solar variations. As has already been seen, the daily SBUV/2 solar irradiance measurements continue the only long-term UV solar spectral irradiance data record, now dating back over one and one-half solar cycles, to 1978. The measurements made by the SBUV/2 instruments are unique - there are presently no other instruments that will likely provide such measurements well into the next century. **It is thus recommended that the daily SBUV/2 sweep mode solar irradiance measurements (or, for the NOAA-14 instrument, the replacement discrete mode solar irradiance measurements at a set of wavelengths selected for solar monitoring) be continued.**

5. ACKNOWLEDGMENTS

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Table 1

RECOMMENDED WAVELENGTHS AND GRATING POSITIONS FOR THE NOAA-14 SBUV/2 SOLAR IRRADIANCE MEASUREMENTS

CHANNEL NUMBER	OZONE WAVELENGTHS (ZIG ZAG)	Mg II WAVELENGTHS (ALTERNATE SET)	SOLAR MONITORING WAVELENGTHS
1	251.985 (526)	276.771 (193)	181.631 (1454)
2	273.511 (237)	279.951 (150)	199.301 (1223)
3	287.623 (46)	283.127 (107)	203.341 (1170)
4	292.257 (-17)	276.771 (193)	207.377 (1117)
5	297.539 (-89)	279.951 (150)	211.407 (1064)
6	301.930 (-149)	283.127 (107)	215.431 (1011)
7	339.836 (-673)	276.771 (193)	219.450 (958)
8	305.801 (-202)	279.951 (150)	251.985 (526)
9	312.500 (-294)	283.127 (107)	285.192 (79)
10	317.509 (-363)	276.771 (193)	290.199 (11)
11	331.228 (-553)	279.951 (150)	393.395 (-1435)
12	339.836 (-673)	283.127 (107)	395.393 (-1464)
Sweep Start	406.226 (-1622)	406.226 (-1622)	406.226 (-1622)
4-Step Start	255.649 (477)	255.649 (477)	255.649 (477)
Position Mode	399.998 (-1531)	199.987 (1214)	300.029 (-123)

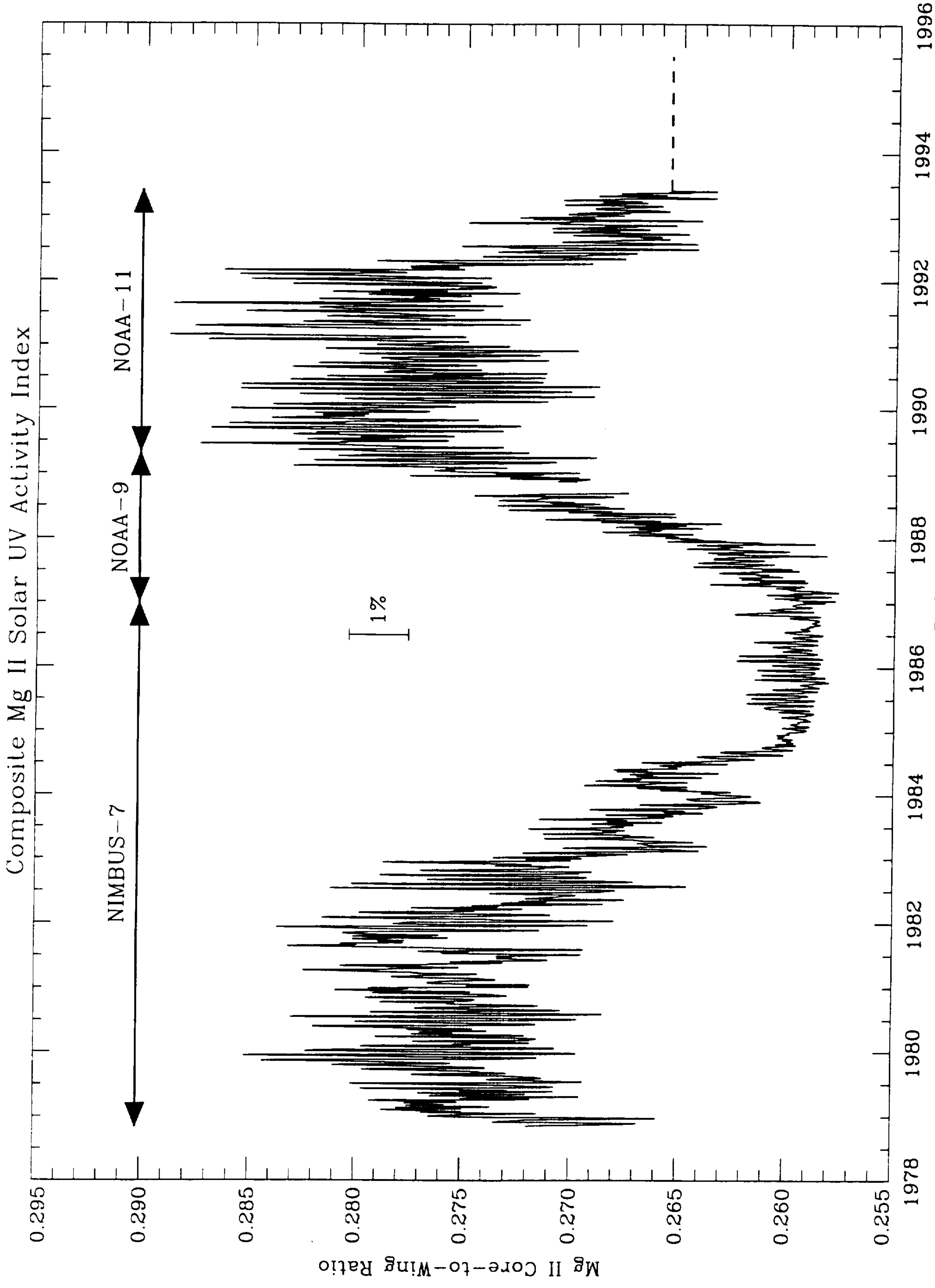
Table 2

Mg II INDEX USERS

(Requests during 1994-1995; recent publications)

Atmosphere	**Solar**
Guy Brasseur, *NCAR*	Dave Bouwer, *NOAA SEL*
Linwood Callis, *NASA Langley*	Richard Cebula, *HSTX/GSFC*
Sushil Chandra, *NASA Goddard*	Matthew DeLand, *HSTX/GSFC*
John DeLuisi, *NOAA/ERL/ARL*	Richard Donnelly, *Solar Radiation Research*
Gian Paolo Gobbi, *Ist. Fisica Atmosfera [Italy]*	Judith Lean, *Naval Research Laboratory*
Kjell Henriksen, *The Auroral Obs. [Norway]*	Julius London, *U. Colorado*
Ernest Hilsenrath, *NASA Goddard*	Ann Mecherikunnel, *NASA Goddard*
Stacey Hollandsworth, *ARC/GSFC*	Judit Pap, *Jet Propulsion Laboratory*
Lon Hood, *U. Arizona*	Dianne Prinz, *Naval Research Laboratory*
Theresa Huang, *NCAR*	Gary Rottman, *NCAR/HAO*
Gerald Keating, *NASA Langley*	Mosalam Shaltout, *NRIAG [Egypt]*
Phillipe Keckhut, *Service d'Aeronomie du CNRS [France]*	Willie Soon, *Center for Astrophysics/Harvard*
Richard McPeters, *NASA Goddard*	Chris St. Cyr, *NASA Goddard*
Michael Newchurch, *U. Alabama (Huntsville)*	Oran White, *NCAR/HAO*
Valentin C. Roldugin, *Apatity Academy, Polar Geophysical Institute [Russia]*	Thomas Woods, *NCAR/HAO*
Klairie Tourpali, *Aristotle Univ. [Greece]*	

Figure 1



Composite Mg II Solar UV Activity Index
NIMBUS-7
NOAA-9
NOAA-11
1%
DATE
Mg II Core-to-Wing Ratio
0.295
0.290
0.285
0.280
0.275
0.270
0.265
0.260
0.255
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996

Figure 2

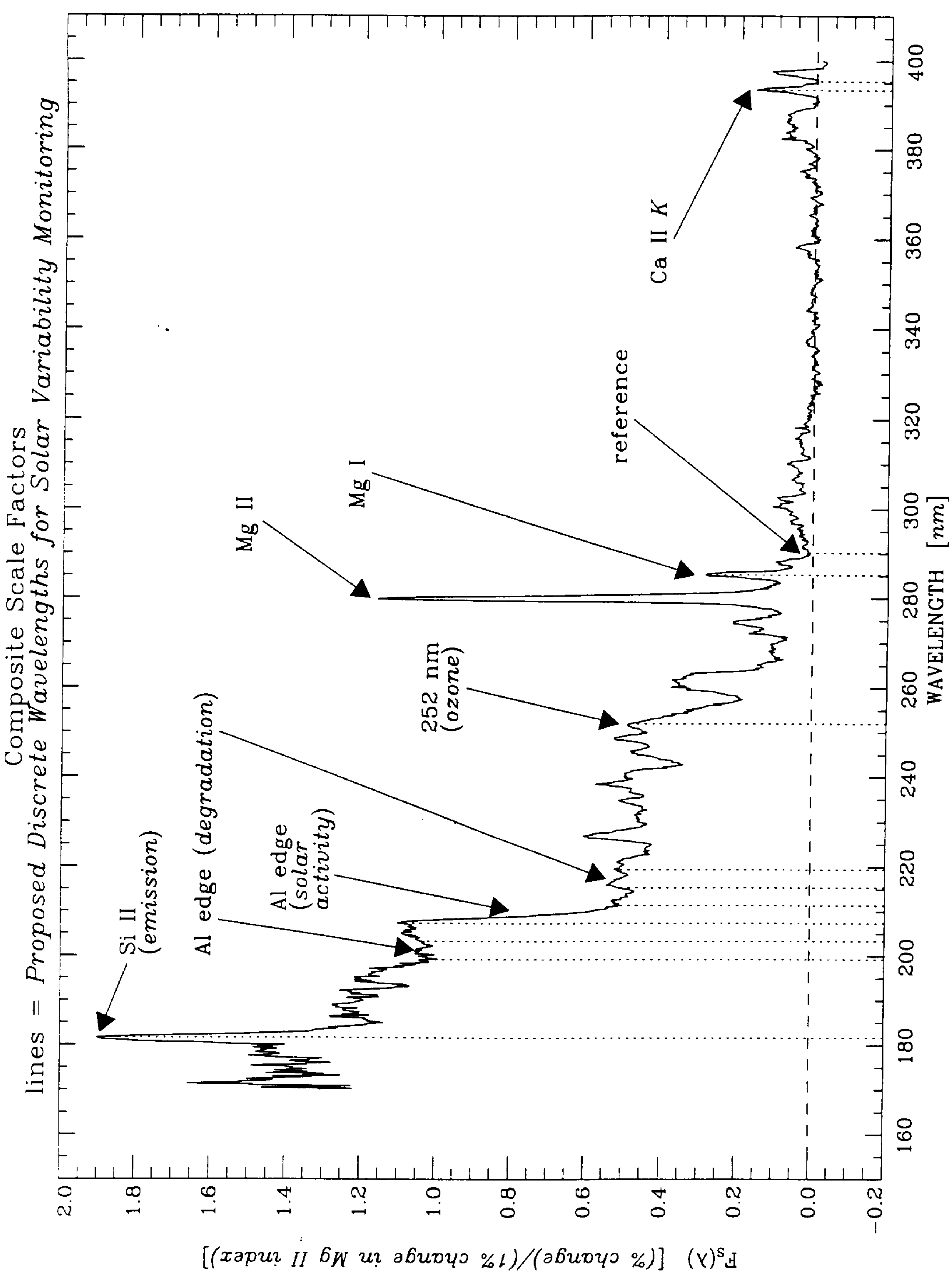
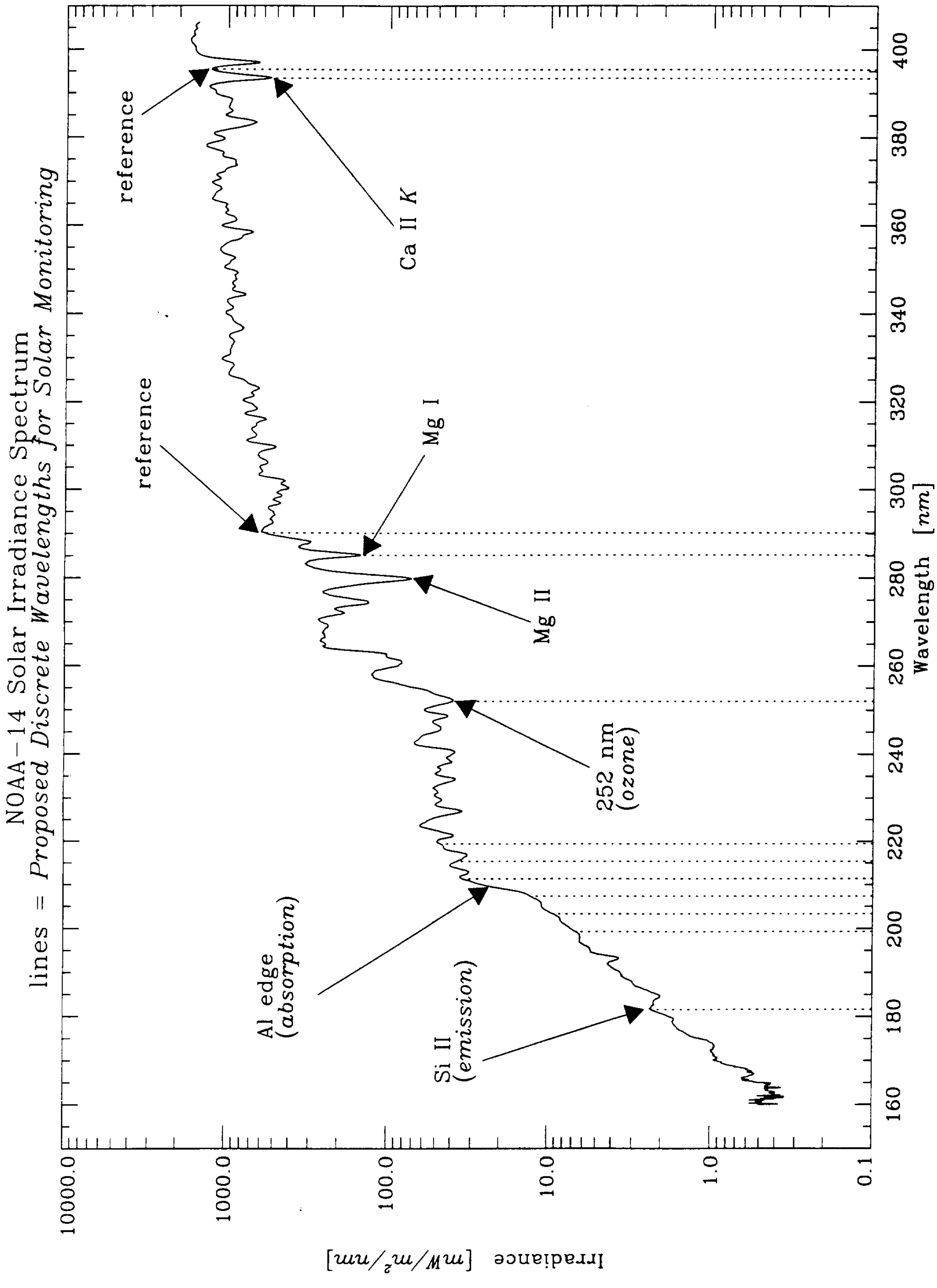

Composite Scale Factors
lines = Proposed Discrete Wavelengths for Solar Variability Monitoring
Si II (emission)
Al edge (degradation)
Al edge (solar activity)
252 nm (ozone)
Mg II
Mg I
reference
Ca II K
WAVELENGTH [nm]
160
180
200
220
240
260
280
300
320
340
360
380
400
F_S(λ) [(% change)/(1% change in Mg II index)]
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2

Figure 3



NOAA-14 Solar Irradiance Spectrum
lines = *Proposed Discrete Wavelengths for Solar Monitoring*
reference
Ca II *K*
reference
Mg I
Mg II
252 nm
(*ozone*)
Al edge
(*absorption*)
Si II
(*emission*)
Wavelength [*nm*]
160
180
200
220
240
260
280
300
320
340
360
380
400
Irradiance [$mW/m^2/nm$]
10000.0
1000.0
100.0
10.0
1.0
0.1