RevMexAA (Serie de Conferencias), **7**, 180–185 (1998)

PRECISION WAVELENGTHS FOR EXPECTED EMISSION LINES IN HIGH-REDSHIFT GALAXIES AND QUASARS

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RESUMEN

Se listan longitudes de onda precisas —con exactitudes de 0.01 Å— de las líneas de emisión más intensas ultravioleta, que se espera en galaxias (incluyendo regiones de formación estelar, galaxias Seyfert y radiogalaxias) así como en cuasares, para usarse en los espectros UV ópticos observados.

ABSTRACT

Precision wavelengths, accurate to 0.01 Å, are listed for the strongest expected ultraviolet emission lines in galaxies (including star-formation regions, Seyfert galaxies and radio galaxies) and quasars, for use in spectra observed either in the UV or optical spectral regions.

Key words: **GALAXIES: QUASARS: EMISSION LINES — LINE: IDENTIFICATION — ULTRAVIOLET: GENERAL**

1. INTRODUCTION

Many years ago, I prepared and published a paper on the expected ultraviolet emission-line spectrum of a gaseous nebula (Osterbrock 1963). It was intended to help in planning for some of the early space-astronomy programs at the University of Wisconsin. However, that paper also turned out to be quite useful for observers with ground-based telescopes, as a list of potential identifications for lines observed in the redshifted spectra of what were then considered distant quasars.

At present, with large telescopes and sensitive CCDs, it is possible to observe much fainter galaxies at considerably larger redshifts. Although Lα will probably remain the emission line of choice for measuring redshifts, it will always be important to measure other lines as well. With the *Hubble Space Telescope* it is possible to obtain the spectra of faint galaxies into the ultraviolet region.

Hence, I have updated the original list and extended it further into the ultraviolet. Also, with the advent of large-format CCDs, echelle spectrographs providing fairly high spectral resolution are increasingly coming into use. Hence I have aimed for a precision of 0.01 Å in the wavelengths.

The data are largely from laboratory spectroscopy of plasmas, and partly from space observations of gaseous nebulae and of the sun (mostly the "transition zone" or upper chromosphere) as listed in the references.

2. DATA INCLUDED

This list is intended for use by galaxy, quasar, and cosmology specialists who are not necessarily emission-line experts. The strongest expected collisionally-excited lines are listed separately by stage of ionization, and within it by excitation potential. Within each multiplet, the lines are distinguished as permitted, semi-forbidden (electric-dipole allowed but spin-forbidden or intercombination), or forbidden (magnetic-dipole and electric- and magnetic- quadrupole) by no, one or two square brackets (Osterbrock & Parker 1966). The expected strongest line in each multiplet is marked with an asterisk for "typical" densities in star-forming regions or narrow-line regions of AGNs (of order 10^4 to 10^6 cm^{-3}). In C III, N IV, O V and Si III, the forbidden $^1S_0$–$^3P_2$ line is stronger at low density, and the semi-forbidden $^1S_0$–$^3P_1$ line at high density (Osterbrock 1970; Keenan et al. 1992, 1995). The critical densities are just over 10^4 cm^{-3} and so both lines are marked with asterisks.

Only ultraviolet lines with $\lambda < 3000$ Å are included in the list. The expected lines with longer wavelengths are included in numerous other readily available lists. All wavelengths are given in S.T.P. air for $\lambda > 2000$ Å and in vacuum for $\lambda < 2000$ Å. This is the standard convention used in all physics books, journals and references. For high-redshift objects, wavelengths measured in air at the telescope may be transformed to vacuum wavelengths using the formulae of Edlén (1953, 1966), then reduced to vacuum rest wavelengths using known or measured z, then transformed back to air wavelengths if $\lambda > 2000$ Å.

Although most observable emission-line gas is expected to be optically thick for $\lambda < 912$ Å, this is not invariably the case. Therefore, a few expected strong lines with 300 Å $< \lambda <$ 912 Å are listed and it may be worthwhile to look for them.

3. TABLE

The wavelengths are listed for individual lines in Table 1, the appendix to this paper. The ionization potential of each ion is listed in its heading, and the excitation potential is listed for each multiplet, both in electron volts. The references to the sources of the wavelengths are listed in a special reference section below. I am particularly grateful to Dr. Uri Feldman and his collaborators for use of the results published in their paper, still in press, giving many ultraviolet wavelengths measured in the solar corona by the SUMER instrument in SOHO, and to Dr. Hien D. Tran for stimulating discussions of emission-line identifications in AGNs. I also wish to thank the Natural Science Foundation for partial support of this research under Grant No. AST 91-23547.

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APPENDIX

WAVELENGTHS FOR INDIVIDUAL LINES

TABLE 1

ULTRAVIOLET EMISSION LINES EXPECTED IN A HIGH REDSHIFT GALAXY OR QUASAR

Ion	Transition	λ
C II $2s^22p\ ^2P^0$ I.P. = 24.4 eV		
$2s^22p\ ^2P^0 - 2s2p^2\ ^4P$ E.P. = 5.3 eV		
C II]	$^2P_{1/2}{}^0 - {}^4P_{3/2}$	2323.50
C II]	$^2P_{1/2}{}^0 - {}^4P_{1/2}$	2324.69
C II]	$^2P_{3/2}{}^0 - {}^4P_{5/2}$	2325.40*
C II]	$^2P_{3/2}{}^0 - {}^4P_{3/2}$	2325.93
C II]	$^2P_{3/2}{}^0 - {}^4P_{5/2}$	2328.12
$2s^22p\ ^2P - 2s2p^2\ ^2D$ E.P. = 9.3 eV		
C II	$^2P_{1/2}{}^0 - {}^2D_{3/2}$	1334.53
C II	$^2P_{3/2}{}^0 - {}^2D_{3/2}$	1355.66
C II	$^2P_{3/2}{}^0 - {}^2D_{5/2}$	1335.71*
$2s^22p\ ^2P^0 - 2s2p^2\ ^2S$ E.P. = 12.0 eV		
C II	$^2P_{1/2}{}^0 - {}^2S_{1/2}$	1036.34
C II	$^2P_{3/2}{}^0 - {}^2S_{1/2}$	1037.02*
C III $2s^2\ ^1S$ I.P. = 47.9 eV		
$2s^2\ ^1S - 2s2p\ ^3P^0$ E.P. = 6.5 eV		
[C III]	$^1S_0 - {}^3P_2{}^0$	1908.73*
C III]	$^1S_0 - {}^3P_1{}^0$	1906.68*
$2s^2\ ^1S - 2s2p\ ^1P^0$ I.P. = 12.6 eV		
C III	$^1S_0 - {}^1P_1{}^0$	977.02
C IV $2s\ ^2S$ I.P. = 64.5 eV		
$2s\ ^2S - 2p\ ^2P^0$ E.P. = 8.0 eV		
C IV	$^2S_{1/2} - {}^2P_{3/2}{}^0$	1548.19*
C IV	$^2S_{1/2} - {}^2P_{1/2}{}^0$	1550.77

Ion	Transition	λ
N II $2s^22p^2\ ^3P$ I.P. = 29.6 eV		
$2s^22p^2\ ^3P - 2s\ 2p^3\ ^5S^0$ E.P. = 8.0 eV		
N II]	$^3P_1 - {}^5S_2{}^0$	2139.01
N II]	$^3P_2 - {}^5S_2{}^0$	2142.77*
$2s^22p^2\ ^3P - 2s2p^3\ ^3D^0$ E.P. = 11.4 eV		
N II	$^3P_0 - {}^3D_1{}^0$	1083.99
N II	$^3P_1 - {}^3D_1{}^0$	1084.56
N II	$^3P_1 - {}^3D_2{}^0$	1084.58
N II	$^3P_2 - {}^3D_1{}^0$	1085.53
N II	$^3P_2 - {}^3D_2{}^0$	1085.55
N II	$^3P_2 - {}^3D_3{}^0$	1085.70*
$2s^22p^2\ ^3P - 2s2p^3\ ^3P^0$ E.P. = 13.6 eV		
N II	$^3P_0 - {}^3P_1{}^0$	915.61
N II	$^3P_1 - {}^3P_0{}^0$	915.96
N II	$^3P_1 - {}^3P_1{}^0$	916.02
N II	$^3P_1 - {}^3P_2{}^0$	916.01
N II	$^3P_2 - {}^3P_1{}^0$	916.71
N II	$^3P_2 - {}^3P_2{}^0$	916.70*
N III $2s^22p\ ^2P^0$ I.P. = 47.4 eV		
$2s^22p\ ^2P^0 - 2s2p^2\ ^4P$ E.P. = 7.1 eV		
N III]	$^2P_{1/2}{}^0 - {}^4P_{3/2}$	1746.82
N III]	$^2P_{1/2}{}^0 - {}^4P_{1/2}$	1748.65
N III]	$^2P_{3/2}{}^0 - {}^4P_{5/2}$	1749.67*
N III]	$^2P_{3/2}{}^0 - {}^4P_{3/2}$	1752.16
N III]	$^2P_{3/2}{}^0 - {}^4P_{1/2}$	1754.00
$2s^22p\ ^2P^0 - 2s2p^2\ ^2D$ E.P. = 12.5 eV		
N III	$^2P_{1/2}{}^0 - {}^2D_{3/2}$	989.80
N III	$^2P_{3/2}{}^0 - {}^2D_{3/2}$	991.51
N III	$^2P_{3/2}{}^0 - {}^2D_{5/2}$	991.58*

TABLE 1 - (CONTINUED)

Ion	Transition	λ
N IV $2s^2\ ^1S$ I.P. = 77.5 eV		
$2s^2\ ^1S - 2s2p\ ^3P^0$ E.P. = 8.3 eV		
[N IV]	$^1S_0 - {}^3P_2{}^0$	1483.21*
N IV]	$^1S_0 - {}^3P_1{}^0$	1486.50*
$2s^2\ ^1S - 2s2p\ ^1P^0$ E.P. = 16.2 eV		
N IV	$^1S_0 - {}^1P_1{}^0$	765.15
N V $2s\ ^2S$ I.P. = 97.9 eV		
$2s\ ^2S - 2p\ ^2P^0$ E.P. = 10.0 eV		
N V	$^2S_{1/2} - {}^2P_{3/2}{}^0$	1238.82*
N V	$^2S_{1/2} - {}^2P_{1/2}{}^0$	1242.80
O II $2s^22p^3\ ^4S^0$ I.P. = 35.1 eV		
$2s^22p^3\ ^4S^0 - 2s^22p^3\ ^2P^0$ E.P. = 5.0 eV		
[O II]	$^4S_{3/2}{}^0 - {}^2P_{1/2}{}^0$	2470.21
[O II]	$^4S_{3/2}{}^0 - {}^2P_{3/2}{}^0$	2470.33
$2s^22p^3\ ^4S^0 - 2s2p^4\ ^4P$ E.P. = 14.8 eV		
O II	$^4S_{3/2}{}^0 - {}^4P_{5/2}$	834.46*
O II	$^4S_{3/2}{}^0 - {}^4P_{3/2}$	833.33
O II	$^4S_{3/2}{}^0 - {}^4P_{1/2}$	832.75
O III $2s^22p^2\ ^3P$ I.P. = 54.9 eV		
$2s^22p^2\ ^3P - 2s^22p^2\ ^1S$ E.P. = 5.4 eV		
[O III]	$^3P_1 - {}^1S_0$	2320.95
$2s^22p^2\ ^3P - 2s2p^3\ ^5S^0$ E.P. = 7.5 eV		
O III]	$^3P_1 - {}^5S_2{}^0$	1660.81
O III]	$^3P_2 - {}^5S_2{}^0$	1666.15*

Ion	Transition	λ
O IV $2s^22p\ ^2P^0$ I.P. = 77.4 eV		
$2s^22p\ ^2P^0 - 2s\ 2p^2\ ^4P$ E.P. = 8.8 eV		
O IV]	$^2P_{1/2}{}^0 - {}^4P_{3/2}$	1397.23
O IV]	$^2P_{1/2}{}^0 - {}^4P_{1/2}$	1399.78
O IV]	$^2P_{3/2}{}^0 - {}^4P_{5/2}$	1401.16*
O IV]	$^2P_{3/2}{}^0 - {}^4P_{3/2}$	1404.81
O IV]	$^2P_{3/2}{}^0 - {}^4P_{1/2}$	1407.38
O V $2s^2\ ^1S$ I.P. = 113.9 eV		
$2s^2\ ^1S - 2s2p\ ^3P^0$ E.P. = 10.2 eV		
[O V]	$^1S_0 - {}^3P_2{}^0$	1213.81*
O V]	$^1S_0 - {}^3P_1{}^0$	1218.34*
O VI $2s\ ^2S$ I.P. = 138.1 eV		
$2s\ ^2S - 2p\ ^2P^0$ E.P. = 10.2 eV		
O VI	$^2S_{1/2} - {}^2P_{3/2}{}^0$	1031.91*
O VI	$^2S_{1/2} - {}^2P_{1/2}{}^0$	1037.61
Ne III $2s^22p^4\ ^3P$ I.P. = 63.5 eV		
$2s^22p^4\ ^3P - 2s^22p^4\ ^1S$ E.P. = 6.9 eV		
[Ne III]	$^3P_1 - {}^1S_0$	1814.63
Ne IV $2s^22p^3\ ^4S^0$ I.P. = 97.1 eV		
$2s^22p^3\ ^4S^0 - 2s^22p^3\ ^2D^0$ E.P. = 5.1 eV		
[Ne IV]	$^4S_{3/2}{}^0 - {}^2D_{3/2}{}^0$	2421.84*
[Ne IV]	$^4S_{3/2}{}^0 - {}^2D_{5/2}{}^0$	2424.47
$2s^22p^3\ ^4S^0 - 2s^22p^3\ ^2P^0$ E.P. = 7.7 eV		
[Ne IV]	$^4S_{3/2}{}^0 - {}^2P_{3/2}{}^0$	1601.47*
[Ne IV]	$^4S_{3/2}{}^0 - {}^2P_{1/2}{}^0$	1607.63

TABLE 1 - (CONTINUED)

Ion	Transition	λ
Ne V $2s^22p^2\ ^3P$ I.P. = 126.2 eV		
	$2s^22p^2\ ^3P - 2s^22p^2\ ^1S$ E.P. = 7.9 eV	
[Ne V]	$^3P_1 - {}^1S_0$	1574.60
	$2s^22p^2\ ^1D - 2s^22p^2\ ^1S$ E.P. = 7.9 eV	
[Ne V]	$^1D_2 - {}^1S_0$	2974.79
	$2s^22p^2\ ^3P - 2s2p^3\ ^5S^0$ E.P. = 11.0 eV	
Ne V]	$^3P_1 - {}^5S_2^0$	1136.51
Ne V]	$^3P_2 - {}^5S_2^0$	1145.61*
Ne VI $2s^22p\ ^2P^0$ I.P. = 157.9 eV		
	$2s^22p\ ^2P^0 - 2s2p^2\ ^4P$ E.P. = 12.3 eV	
Ne VI]	$^2P_{1/2}^0 - {}^4P_{3/2}$	992.68
Ne VI]	$^2P_{1/2}^0 - {}^4P_{1/2}$	997.03
Ne VI]	$^2P_{3/2}^0 - {}^4P_{5/2}$	998.18*
Ne VI]	$^2P_{3/2}^0 - {}^4P_{3/2}$	1005.70
Ne VI]	$^2P_{3/2}^0 - {}^4P_{1/2}$	1010.20
Mg II 3s ^2S I.P. = 15.0 eV		
	3s ^2S – 3p $^2P^0$ E.P. = 4.4 eV	
Mg II	$^2S_{1/2} - {}^2P_{3/2}^0$	2795.92*
Mg II	$^2S_{1/2} - {}^2P_{1/2}^0$	2802.70
Mg V $2s^22p^4\ ^3P$ I.P. = 141.3 eV		
	$2s^22p^4\ ^3P - 2s^22p^4\ ^1D$ E.P. = 4.5 eV	
[Mg V]	$^3P_2 - {}^1D_2$	2783.17*
[Mg V]	$^3P_1 - {}^1D_2$	2928.29
	$2s^22p^4\ ^3P - 2s^22p^4\ ^1S$ E.P. = 9.6 eV	
[Mg V]	$^3P_1 - {}^1S_0$	1324.44

Ion	Transition	λ
Mg VI $2s^22p^3\ ^4S^0$ I.P. = 186.5 eV		
	$2s^22p^3\ ^4S^0 - 2s^22p^3\ ^2D^0$ E.P. = 6.8 eV	
[Mg VI]	$^4S_{3/2}^0 - {}^2D_{3/2}^0$	1805.94
[Mg VI]	$^4S_{3/2}^0 - {}^2D_{5/2}^0$	1806.66
	$2s^22p^3\ ^4S^0 - 2s^22p^3\ ^2P^0$ E.P. = 10.4 eV	
[Mg VI]	$^4S_{3/2}^0 - {}^2P_{3/2}^0$	1190.07*
[Mg VI]	$^4S_{3/2}^0 - {}^2P_{1/2}^0$	1191.62
Mg VII $2s^22p^2\ ^3P$ I.P. = 225.0 eV		
	$2s^22p^2\ ^3P - 2s^22p^2\ ^1D$ E.P. = 5.1 eV	
[Mg VII]	$^3P_1 - {}^1D_2$	2508.13
[Mg VII]	$^3P_2 - {}^1D_2$	2627.59*
	$2s^22p^2\ ^3P - 2s^22p^2\ ^1S$ E.P. = 10.5 eV	
[Mg VII]	$^3P_1 - {}^1S_0$	1189.82*
	$2s^22p^2\ ^1D - 2s^22p^2\ ^1S$ E.P. = 10.5 eV	
[Mg VII]	$^1D_2 - {}^1S_0$	2262.36
Si II $3s^23p\ ^2P^0$ I.P. = 16.3 eV		
	$3s^23p\ ^2P^0 - 3s3p^2\ ^4P$ E.P. = 5.3 eV	
Si II]	$^2P_{1/2}^0 - {}^4P_{3/2}$	2328.51
Si II]	$^2P_{1/2}^0 - {}^4P_{1/2}$	2334.40
Si II]	$^2P_{3/2}^0 - {}^4P_{5/2}$	2334.61*
Si II]	$^2P_{3/2}^0 - {}^4P_{3/2}$	2344.20
Si II]	$^2P_{3/2}^0 - {}^4P_{1/2}$	2350.17
	$3s^23p\ ^2P^0 - 3s3p^2\ ^2D$ E.P. = 6.3 eV	
Si II	$^2P_{1/2}^0 - {}^2D_{3/2}$	1808.00
Si II	$^2P_{3/2}^0 - {}^3D_{3/2}$	1817.45
Si II	$^2P_{3/2}^0 - {}^3D_{5/2}$	1816.92*

TABLE 1 - (CONTINUED)

Ion	Transition	λ
	Si II $3s^23p\ ^2P^0$ I.P. = 16.3 eV (cont.)	
	$3s^23p\ ^2P^0 - 3s^24s\ ^2S$ E.P. = 8.1 eV	
Si II	$^2P_{1/2}{}^0 - {}^2S_{1/2}$	1526.72
Si II	$^2P_{3/2}{}^0 - {}^2S_{1/2}$	1533.45*
	$3s^23p\ ^2P^0 - 3s3p^2\ ^2S$ E.P. = 9.5 eV	
Si II	$^2P_{1/2}{}^0 - {}^2S_{1/2}$	1304.37
Si II	$^2P_{3/2}{}^0 - {}^2S_{1/2}$	1309.27*
	$3s^23p\ ^2P^0 - 3s^23d\ ^2D$ E.P. = 9.8 eV	
Si II	$^2P_{1/2}{}^0 - {}^2D_{3/2}$	1260.42
Si II	$^2P_{3/2}{}^0 - {}^2D_{3/2}$	1265.02
Si II	$^2P_{3/2}{}^0 - {}^2D_{5/2}$	1264.73*
	$3s^23p\ ^2P^0 - 3s3p^2\ ^2P$ E.P. = 10.4 eV	
Si II	$^2P_{1/2}{}^0 - {}^2P_{3/2}$	1190.42
Si II	$^2P_{1/2}{}^0 - {}^2P_{1/2}$	1198.23
Si II	$^2P_{3/2}{}^0 - {}^2P_{3/2}$	1194.50*
Si II	$^2P_{3/2}{}^0 - {}^2P_{1/2}$	1197.39
	Si III $3s^2\ ^1S$ I.P. = 33.5 eV	
	$3s^2\ ^1S - 3s3p\ ^3P^0$ E.P. = 6.6 eV	
[Si III]	$^1S_0 - {}^3P_2{}^0$	1882.71*
Si III]	$^1S_0 - {}^3P_1{}^0$	1892.04*
	$3s^2\ ^1S - 3s3p\ ^1P^0$ E.P. = 10.3 eV	
Si III	$^1S_0 - {}^1P_1{}^0$	1206.51
	Si IV $3s\ ^2S$ I.P. = 45.1 eV	
	$3s\ ^2S - 3p\ ^2P$ E.P. = 8.8 eV	
Si IV	$^2S_{1/2} - {}^2P_{3/2}$	1393.76*
Si IV	$^1S_{1/2} - {}^2P_{1/2}$	1402.77

Ion	Transition	λ
	S II $3s^23p^3\ ^4S^0$ I.P. = 23.4 eV	
	$3s^23p^3\ ^4S^0 - 3s3p^4\ ^4P$ E.P. = 9.9 eV	
S II	$^4S_{3/2}{}^0 - {}^4P_{5/2}$	1259.53*
S II	$^4S_{3/2}{}^0 - {}^4P_{3/2}$	1253.79
S II	$^4S_{3/2}{}^0 - {}^4P_{1/2}$	1250.50
	S III $3s^23p^2\ ^3P$ I.P. = 35.0 eV	
	$3s^23p^2\ ^3P - 3s3p^3\ ^5S^0$ E.P. = 10.4 eV	
S III]	$^3P_1 - {}^5S_2{}^0$	1713.12
S III]	$^3P_2 - {}^5S_2{}^0$	1728.94*
	S IV $3s^23p\ ^2P^0$ I.P. = 47.3 eV	
	$3s^23p\ ^2P^0 - 3s3p^2\ ^4P$ E.P. = 9.0 eV	
S IV]	$^2P_{1/2}{}^0 - {}^4P_{3/2}$	1398.13
S IV]	$^2P_{1/2}{}^0 - {}^4P_{1/2}$	1404.89
S IV]	$^2P_{3/2}{}^0 - {}^4P_{5/2}$	1406.04*
S IV]	$^2P_{3/2}{}^0 - {}^4P_{3/2}$	1416.95
S IV]	$^2P_{3/2}{}^0 - {}^4P_{1/2}$	1423.92
	S V $3s^2\ ^1S$ I.P. = 72.5 eV	
	$3s^2\ ^1S - 3s3p\ ^3P^0$ E.P. = 10.3 eV	
[S V]	$^1S_0 - {}^3P_2{}^0$	1187.05
S V]	$^1S_0 - {}^3P_1{}^0$	1199.18
	S VI $3s\ ^2S$ I.P. = 88.0 eV	
	$3s\ ^2S - 3p\ ^2P^0$ E.P. = 13.2 eV	
S VI	$^1S_{1/2} - {}^2P_{3/2}$	933.38*
S VI	$^1S_{1/2} - {}^2P_{1/2}$	944.52