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The National Synchrotron Light Source in the Infra-red Region*

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ABSTRACT

We present a discussion of the utilization of the NSLS in the 1-100 micron infra-red spectral region. A comparison is made of the respective brightnesses of the NSLS and of black-body sources. The way in which each source may be utilized with a monochromator is discussed and comparative exit slit brightnesses are calculated for selected cases.

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1. Introduction

The purpose of this paper is to examine the characteristics of synchrotron radiation in the infra-red spectral region from 1-100 microns and compare it with a 2000°K black body source. The comparison is made for the National Synchrotron Light Source (NSLS) 700MeV storage ring under construction at Brookhaven National Laboratory, Upton, New York[1], whose bending radius is 1.91 meters. Five wavelengths, namely 1, 2.5, 10, 30 and 100μm are chosen for the study. 2.5μm is near the 2000°K black body peak. The calculations are made primarily on the basis of brightness so that they may be applied rather generally to comparisons involving beam lines of various acceptances. We define brightness as the flux per unit solid angle per unit area of (emitting) surface. This quantity is a particularly important one for example in studies of surface vibrations where the sample acceptance is very small. In this case, the matching to a black body source is less efficient than with a more collimated source such as a laser or synchrotron storage ring. Other factors such as stability which may also influence the comparison are discussed qualitatively at the end.

Previous comparisons of a similar nature have been made by Stevenson[2,3], and Lagarde[4,5]. It has been pointed out recently by Chabal[6] that synchrotron light sources are particularly attractive at longer wavelengths since the brightness falls off roughly at $\lambda^{-5/2}$ rather than λ^{-4} as in the black body case.

2. Characteristics of the NSLS Synchrotron Radiation Source

Synchrotron storage rings are being used increasingly as sources of radiation in the X-ray and vacuum ultra-violet spectral ranges. Good reviews[7,8] are now available which summarize the general characteristics of the radiation.

(a) Angular Divergence

For small horizontal acceptance angles synchrotron radiation from the NSLS appears to come from a source whose height y is .2mm and whose width x is 1mm. This (relavistic) source does not radiate uniformly into 2π steradians in the laboratory frame but instead the radiation is emitted strongly only in the forward direction, that is tangential to the electron orbit. The angular spread always fills the horizontal aperture ΨH defined by the mechanical size of the first optic. In the vertical direction, the angular spread is a function of wavelength. In a complete description the brightness of the source at a given wavelength, λ, varies with vertical angle Ψv from the orbit plane. For this preliminary comparison we will assume that the brightness is constant up to a value $\pm\Psi_{vr}$ which is given by the Lorentz transformation[9] as

$$\Psi_{vr} = 1.66.10^{-2}\gamma^{0.28}\left(\frac{\lambda}{\rho}\right)^{.425} .$$

where Ψ_{vr} is in milliradians. λ is the wavlength in Angstroms, ρ the bending radius in meters and γ the ratio of electron mass to its rest mass. (γ = 1957E where E is the electron energy in GeV). For the NSLS 700 MeV ring the values of Ψ_{vr} are given in Table I.

(b) Source Size

Since the radiation vertical divergence angles are rather small, it immediately becomes evident that at longer wavelengths the diffraction limited image size S_{DL} is greater than the .2mm vertical source size or even the 1mm horizontal source size. We assume S_{DL} is given as $\frac{1.22\lambda}{\Psi}$, the diameter of the first dark ring. It follows

(b) Source Size (Cont'd.)

then, that as soon as the synchrotron radiation is imaged in any beam line, its brightness is reduced. Since the radiation has to be imaged to be used, we use the "effective brightness" in the comparison. We note, however, that the small natural source size implies that spatially coherent vertical illumination occurs at the first optic, or sample, at wavelengths greater than 10μm. Spatially coherent illumination is defined to occur if the condition:

$$\lambda \leq s.2.\Psi_{vr}$$

is fulfilled where s is the source height, which is considered to be .2mm for small horizontal acceptance angles.

There is a second important factor which has to be taken account of in considerations of source size. This is the fact that the effective source size increases as Ψ_H increases. The reason for this is readily explained when we realize that if Ψ_H = 50 Mradians, then the source is really 9.6cm of electron orbit. If we then image the front of the source (nearest the first optic) making it our object point, radiation emitted from the back of the source has the effect of blowing up the size of this object. In the horizontal direction the main effect is geometric and essentially wavelength independent. In the vertical direction, the source size blow-up is a strong function of the vertical divergence and hence λ. Continuing our example, if Ψ_H = 50 mradians, we find that x doubles to 2mm and y is approximately tripled to .6mm. Values of the horizontal source size for other values of Ψ_H are shown in Fig. 1. The vertical source size is obtained from Table 2 and Fig. 2 which were taken from reference 9. Similar considerations are treated by M. Howells in this issue.

3. The Black Body Source

For comparison with the synchrotron radiation source we have chosen a black body radiator in the form of a ribbon of dimensions 10mm x 1mm at a temperature of 2000°K. In Table I we have calculated the flux emitted by this source assuming unit emissivity. We have then calculated the brightness (in which the area term divides out) which we have multiplied by two to take account of geometrical effects since we are only collecting radiation near normal to the source.

4. Discussion

A direct comparison of the respective brightnesses of the two sources is given in Table 1. This indicates that the synchrotron radiation source is between two and three orders of magnitude brighter than a black body source in the region 1-100 microns. Whether such higher brightness actually results in higher useful flux at a sample in an experiment depends entirely on the application. There exists a value for the figure of merit (defined in the same units as those for brighness but per resolution element) which for a given $\Delta\lambda$ and a given source geometry corresponds to collecting all the flux. For the synchrotron source this corresponds to a rather small (say f20) instrument. Any improvement in the figure of merit above this value results in no increase in throughput. A further consideration which may reduce the advantage of the higher brightness synchrotron source concerns the diffraction limited resolution. In general, the rather small opening angle of the radiation leads to rather low resolution. Improvements can be made by using an appropriate optical transport line but only at the expense of source matching. Resolving powers available at the NSLS without demagnification (and hence underfilling an entrance slit) lie between 1000 at 1μm and 100 at 100μm for a 0.5 meter instrument at near normal incidence.

4. DISCUSSION (Cont'd.)

An important advantage occurs, however, for synchrotron radiation if the figure of merit for the experiment itself is low. Such is the case, for example, for surface vibrational studies in surface science. Experiments in this area require a well collimated beam with less than a 5° spread in the electric vector with a small (~2mm) image size. Under these circumstances, increasing the figure of merit of the spectrometer (with a black body source) does not result in an increase in signal due to inefficient matching with the experiment.

In the above comparison, we have neglected several points. First, synchrotron radiation is an ultra-high vacuum source and can be used without the need for windows for any experiment in vacuum. Secondly, it is expected to be a very stable source. Rapid ($\leq$.1second) movements of the source itself (the electron beam) or rapid changes in flux caused by beam direction changes are not expected to occur. Slow (1 hour) drifts of up to 0.1 mradians in angle and 10μm in position may occur, but will be much longer than any experimental measuring time interval. Other advantages lie in the fact that it may be less expensive to construct an f20 monochromator (or experiment) than an f5 monochromator. Indeed, it may be possible fairly readily to use a modest sized zone plate monochromator for the infra-red since the beam at 2 meters is approximately 10cm wide. Synchrotron radiation is also highly polarized in the orbit plane, the polarization being a function of wavelength and vertical angle[7-9].

There is one very important point which has been assumed in this paper. That is that all the vertically emitted radiation is collected. The penalty for not achieving this is a considerable reduction in brightness. Consider, for example, using a conventional NSLS beam line which only passes 10 mradians vertically. At 100 μm wavelength only 20% of the

Discussion (Cont'd.)

emitted radiation passes through this aperture. Also with this restriction the diffraction limited source height would be 12.2mm instead of 1.8mm. Thus the brightness of the synchrotron source would be reduced by about 34 times. At 10μm and 30μm wavelengths, the corresponding reductions are 8 times and 16 times.

It should be remembered that all the above comparisons were made assuming a stored current in the NSLS VUV ring of 1 ampere, which is the maximum design current.

It is worth remarking, finally, that devices known as coherent wigglers or undulators[10] inserted into straight sections in storage rings, emit radiation with brightness values up to four orders of magnitude higher than those obtained with the dipole sources discussed in this paper. These devices are expected to play an important role in the future.

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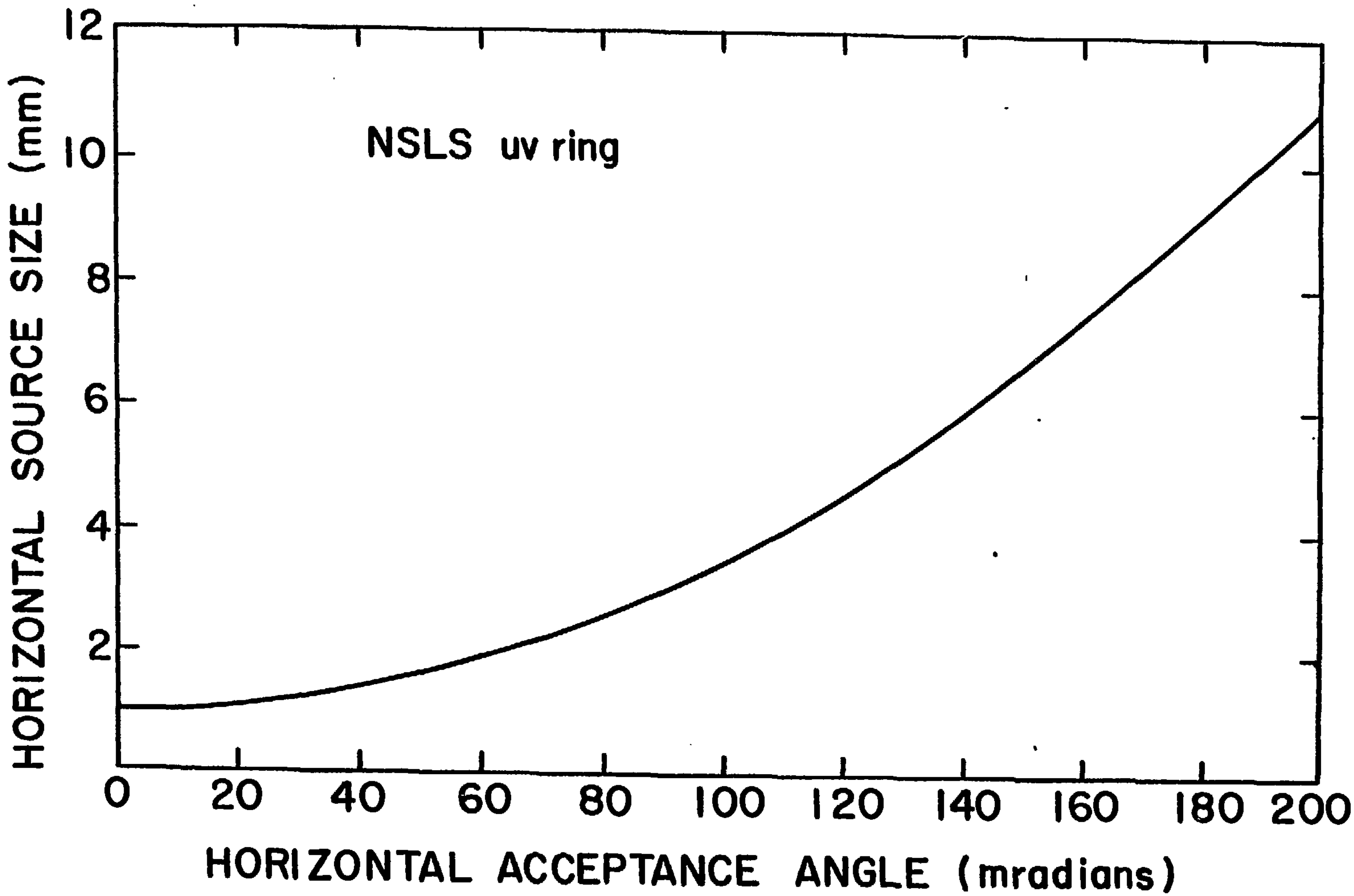

NSLS uv ring
HORIZONTAL SOURCE SIZE (mm)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
140
160
180
200
HORIZONTAL ACCEPTANCE ANGLE (mradians)

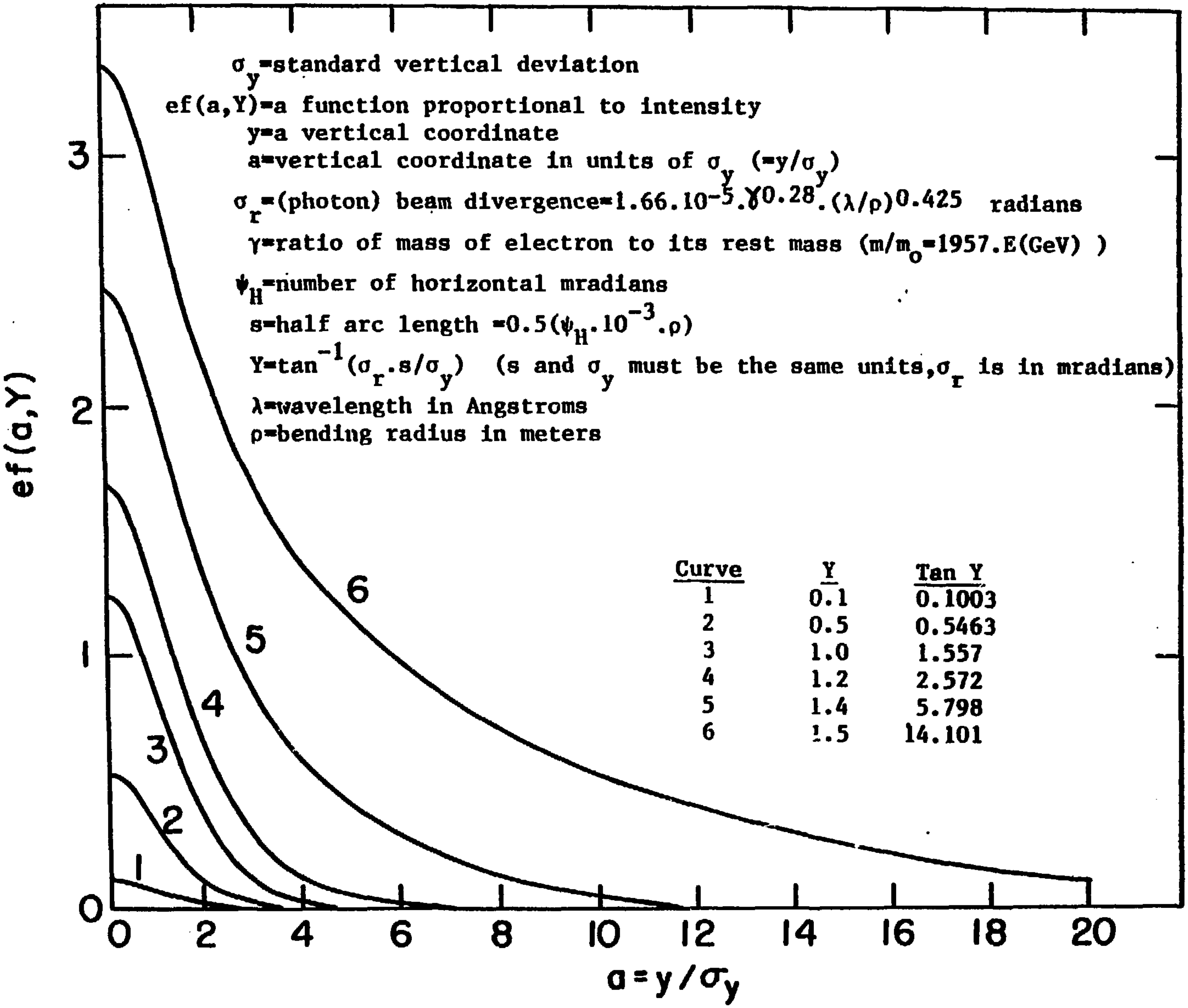
σy=standard vertical deviation
ef(a,Y)=a function proportional to intensity
y=a vertical coordinate
a=vertical coordinate in units of σy (=y/σy)
σr=(photon) beam divergence=1.66.10^-5.γ^0.28.(λ/ρ)^0.425 radians
γ=ratio of mass of electron to its rest mass (m/mo=1957.E(GeV))
ψH=number of horizontal mradians
s=half arc length =0.5(ψH.10^-3.ρ)
Y=tan^-1(σr.s/σy) (s and σy must be the same units,σr is in mradians)
λ=wavelength in Angstroms
ρ=bending radius in meters
Curve Y Tan Y
1 0.1 0.1003
2 0.5 0.5463
3 1.0 1.557
4 1.2 2.572
5 1.4 5.798
6 1.5 14.101
ef(a,Y)
a=y/σy
0
1
2
3
0
2
4
6
8
10
12
14
16
18
20
1
2
3
4
5
6

Fig. 2

Figure Captions

Fig. 1 - The horizontal source size at the NSLS 700MeV ring as a function of horizontal acceptance angle.

Fig. 2 - The intensity distribution ef(a,Y) vertically across the synchrotron source as a function of the vertical coordinate a, and the effect on the ef(a,Y) of increasing Ψ_H.

TABLE I

λ(μm)	NSLS Vert. & Horiz. Radiation Opening Angle (mrads)	NSLS Source Size Vert. & Horiz.(mm) * = Diff. Limited	NSLS Flux Photons Photons / Sec. (Exit Slit Flux)	NSLS Brightness ph/sec/str/cm^2	BB Flux ph/sec	BB Brightness ph/sec/str/cm^2	Brightness NSLS/BB
1	9.6 x 50	300 x 2000	2.6×10^{14}	9.0×10^{19}	1.4×10^{16}	4.5×10^{16}	2000
2.5	14.0 x 50	325 x 2000	2.0×10^{14}	4.3×10^{19}	7.2×10^{16}	2.3×10^{17}	597
10	25.4 x 50	480* x 2000	1.3×10^{14}	1.1×10^{19}	1.8×10^{16}	5.8×10^{16}	184
30	40.4 x 50	906* x 2000	8.0×10^{13}	2.7×10^{18}	2.6×10^{15}	8.3×10^{15}	325
100	76.4 x 50	1809* x 2440*	5.5×10^{13}	3.7×10^{17}	2.5×10^{14}	8.0×10^{14}	463

A comparison between the National Synchrotron Light Source (NSLS) 700MeV ring and a 2000°K 10mm x 11mm black body. In each case, a 0.1% bandwidth is assumed.

TABLE 11 ef(a,Y)

Mantissa following table entry denotes power of ten multiplier.

tan Y	Y \ a	0	0.25	0.5	1.0	1.5	2.0	3.0
.1003	0.1	0.1002	0.9710-1	0.8843-1	0.6086-1	0.3264-1	0.1365-1	1.130-3
.2027	.2	.2013	0.1952	0.1780	0.1229	.6636-1	.2799-1	2.378-3
.3093	.3	.3046	.2955	.2698	.1875	0.1023	.4382-1	3.898-3
.4228	.4	.4111	.3991	.3652	.2561	.1418	.6210-1	5.921-3
.5463	.5	.5222	.5075	.4656	.3302	.1865	.8411-1	8.839-3
.6841	.6	.6396	.6222	.5728	.4119	.2384	0.1116	1.334-2
.8423	.7	.7654	.7455	.6890	.5035	.3001	.1471	2.069-2
1.030	.8	.9022	.8800	.8170	.6082	.3752	.1942	3.314-2
1.260	.9	1.054	1.030	.9607	.7304	.4683	.2579	5.477-2
1.557	1.0	1.226	1.200	1.126	.8759	.5861	.3457	9.277-2
1.965	1.1	1.428	1.400	1.321	1.054	.7389	.4690	1.596-1
2.572	1.2	1.674	1.645	1.562	1.280	.9430	.6456	2.766-1
3.010	1.25	1.821	1.792	1.708	1.420	1.073	.7631	3.649-1
3.602	1.30	1.993	1.964	1.878	1.585	1.229	.9082	4.824-1
4.455	1.35	2.200	2.169	2.083	1.785	1.422	1.091	6.406-1
5.798	1.40	2.458	2.428	2.340	2.039	1.670	1.331	8.588-1
8.238	1.45	2.806	2.775	2.687	2.383	2.009	1.665	1.175
14.101	1.50	3.341	3.310	3.221	2.915	2.539	2.190	1.689
16.428	1.51	3.493	3.462	3.373	3.067	2.691	2.341	1.839
19.670	1.52	3.673	3.642	3.553	3.247	2.870	2.520	2.016

Blank indicates value less than 10^{-6}

Y \ a	4.0	5.0	6.0	7.0	8.0	10	20
0.1	3.452-5						
.2	7.547-5						
.3	1.327-4	1.744-6					
.4	2.259-4	3.536-6					
.5	3.992-4	8.171-6					
.6	7.594-4	2.232-5					
.7	1.574-3	7.124-5	1.957-6				
.8	3.526-3	2.540-4	1.229-5				
.9	8.334-3	9.592-4	8.119-5	4.918-6			
1.0	2.019-2	3.643-3	5.261-4	5.944-5	5.190-6		
1.1	4.874-2	1.332-2	3.142-3	6.289-4	1.057-4	1.725-6	
1.2	1.149-1	4.529-2	1.646-2	5.432-3	1.615-3	1.024-4	
1.25	1.741-1	8.077-2	3.547-2	1.456-2	5.545-3	6.319-4	
1.30	2.615-1	1.407-1	7.325-2	3.652-2	1.733-2	3.316-3	
1.35	3.903-1	2.396-1	1.451-1	8.578-2	4.929-2	1.473-2	3.336-6
1.40	5.817-1	4.014-1	2.770-1	1.895-1	1.280-1	5.557-2	2.365-4
1.45	8.760-1	6.695-1	5.162-1	3.988-1	3.076-1	1.804-1	7.444-3
1.50	1.374	1.148	9.724-1	8.297-1	7.111-1	5.258-1	1.100-1
1.51	1.521	1.293	1.113	9.668-1	8.439-1	6.487-1	1.745-1
1.52	1.697	1.466	1.283	1.133	1.007	8.027-1	2.714-1