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Photon Counts From Stellar Occultation Sources

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Introduction

Many Earth-orbiting satellites contain instruments that are designed to provide measurements from which the vertical distribution of trace constituents in the Earth's atmosphere may be inferred. Many of these (e.g., SAM I and II, SAGE I and II) accomplish this by using the Sun as a source of radiant energy and measure the attenuation of this radiation as the Sun rises and sets with respect to the spacecraft. The line of sight between the spacecraft and the Sun is referred to as the tangent ray. There is a point along the tangent ray where the height of the ray above the Earth's surface is a minimum—the tangent point. This point, projected vertically to the Earth's surface, locates the subtangent point. Most of the attenuation of the solar radiation occurs in the immediate vicinity of the tangent point, and hence the computed number density or mass density of the absorbing material is generally associated geographically with the subtangent point and at the altitude of the tangent point.

For most satellite geometries, during one complete orbital revolution there is one sunrise and one sunset event. (There are no sunrise and sunset events for some geometries in which the orbital plane of the satellite is nearly normal to the Earth-Sun line. These geometries are not considered further in the present paper.) A typical near-Earth satellite completes 14 to 15 orbits per day, and so there are nominally some 10 000 sunrise and sunset events per year. The mission designer is concerned with the global distribution of the subtangent points locating these events, and for some types of missions wants to cover as much of the Earth's surface as possible. Unfortunately, other mission constraints may be, and usually are, imposed on the mission, thus frequently presenting the mission designer with a nonoptimal choice of available design parameters.

The present paper describes a feasibility study that considers the use of stars as radiation energy sources to provide more flexibility to the design of occultation missions for atmospheric probing.

The problem to be addressed in the present study is to investigate the answer to one basic question: Do enough stellar photons reach the detector of the instrument to produce a measurable signal proportional to the incoming photon flux? In order to answer this question, three basic parameters of the system must be examined:

1. What is the number of photons/(cm^2-sec) reaching the collector optics of the radiometer system? This number is independent of the radiometer design and is a function only of the surface temperature of the star, its size, and its distance from the Earth. Assuming 100-percent efficiency in the optics and detector systems, this is the maximum number of photons available to produce a measurable signal. In practice, of course, only a very small fraction of these actually produce signal output.

2. The efficiency of the optical system is *not* 100 percent. So, of all the photons that enter the collector area of the optical system, how many actually reach the detector? This number is a function of the length of the optical path between the collector entrance and the detector, and of the number of times the optical path changes direction or is otherwise interfered with. The largest contributor to the loss of stellar photons is the type and number of filters placed in the optical path to isolate a particular wavelength region. The average collector efficiency is usually of the order of a few percent.

3. Of all the photons that finally reach the detector, how many can actually be detected and correlated with the number entering the collector area and hence related to the incoming radiative flux? This number is primarily a function of the type of detector and of the quantum efficiency of the detector in the wavelength region under study.

Item 1, being instrument independent, is the only part of this three-phased question that can easily be addressed and is the main thrust of the present paper.

Items 2 and 3 are highly dependent on the physical characteristics of a specific collector and detector system and, consequently, can only be addressed meaningfully if reasonable numbers are known or assumed for its performance characteristics.

Analysis

If we assume that a given star radiates as a blackbody and that certain astronomical parameters of the star are known, it is possible to compute the photon flux of the star outside the Earth's atmosphere.

The *spectral flux* emitted by the star at wavelength λ, cm, and surface temperature T_*, K, is (see, for example, Liou 1980)

$$F_\lambda\,(T_*) = \frac{2\pi hc^2}{\lambda^5}\,\frac{1}{\exp\left(\frac{hc}{\lambda kT_*}\right)-1}\quad\frac{\text{erg}}{\text{cm}^2\text{-sec-cm}} \tag{1}$$

where

h Planck's constant, 6.625×10^{-27} erg-sec

c speed of light, 2.9979×10^{10} cm/sec

k Boltzmann's constant, 1.38×10^{-16} erg/K

The energy per photon of this radiation is hc/λ, and thus if we divide equation (1) by this quantity, we get an expression for the photon flux at the surface of the star

$$N_\lambda(T_*) = \frac{2\pi c}{\lambda^4} \frac{1}{\exp\left(\frac{hc}{\lambda k T_*}\right) - 1} \quad \frac{\text{photons}}{\text{cm}^2\text{-sec-cm}} \qquad (2)$$

This expression gives the total number of photons/sec emitted per unit area of the star, per unit wavelength, at the *surface* of the star. If R_* is the radius of the star, the total number of photons/sec emitted from the star in all directions is

$$N_{T_\lambda}\ (T_*) = 4\pi R_*^2\ N_\lambda(T_*) \quad \frac{\text{photons}}{\text{sec-cm}} \qquad (3)$$

If we assume no attenuation of photons in the interstellar medium, the total number of photons/sec given by equation (3) passing through the sphere of radius R_* must be the same passing through *any* sphere centered at the star. In particular, if d_* is the distance of the star from the Earth, then the total number of photons/sec that were emitted by the star, and that cross a unit area at the Earth distance is

$$\begin{aligned} N_*\ (T_*) &= \frac{N_{T_\lambda}\ (T_*)}{4\pi d_*^2} \\ &= \left(\frac{R_*}{d_*}\right)^2 N_\lambda(T_*) \quad \frac{\text{photons}}{\text{cm}^2\text{-sec-cm}} \qquad (4) \end{aligned}$$

Let $\phi(\lambda)$ be the spectral response function of some instrument (or of the human eye) with which we want to measure the energy from the star. Typically, $\phi(\lambda)$ is defined for some definite wavelength region $\Delta\lambda$. It generally has a single maximum somewhere near the center of the band and drops off to zero as the edges of the band are approached and is defined to be zero outside the band. With this function, the total number of photons/sec to which the instrument is potentially responsive is given by

$$N_I(T_*) = \left(\frac{R_*}{d_*}\right)^2 \int_0^\infty \phi(\lambda)\ N_\lambda(T_*)\ d\lambda \quad \frac{\text{photons}}{\text{cm}^2\text{-sec}} \qquad (5)$$

The major problem in evaluating equation (5) is, of course, that we seldom know the radius of the star R_* and may not know its distance from the Earth d_*. However, the ratio R_*/d_* can be estimated if we assume blackbody radiation and if we know two other parameters of the star: its visual magnitude and its surface temperature. The magnitude of a star can be measured directly in any of several wavelength regions—the magnitudes of importance to us are the visual and photographic magnitudes.

The human eye and photographic film have different spectral response functions that peak at different parts of the visible spectrum. The eye is most responsive to radiation around 5290 Å, whereas the spectral response function of photographic film peaks somewhat more toward the blue at about 4250 Å. If we assume that the spectral response functions are flat, then the temperature of the star can be inferred from the visual and photographic magnitudes as follows (much of the remaining development was taken in bits and pieces from essentially two references: Payne-Gaposchkin (1954) and Jeans (1961)—mostly from Jeans): From equation (1) the total energy radiated by the star in the wavelength interval $\lambda_2 - \lambda_1$ is

$$E_T = 4\pi R_*^2 \int_{\lambda_1}^{\lambda_2} \frac{2\pi hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda k T_*}\right)}\ d\lambda \quad \frac{\text{erg}}{\text{sec}} \qquad (6)$$

Near the middle of the visible radiation band, say 5290 Å, and for reasonable stellar surface temperatures of 3000 K to 16 000 K

$$\exp\left(\frac{hc}{\lambda k T_*}\right) >> 1$$

If we invoke this assumption, and use the mean value theorem of integral calculus, we can write equation (6) as

$$E_T \approx 4\pi R_*^2 \left[\frac{2\pi hc^2}{\lambda_o^5} \exp\left(\frac{-hc}{\lambda_o k T_*}\right)\right] (\lambda_2 - \lambda_1) \quad \frac{\text{erg}}{\text{sec}} \qquad (7)$$

where λ_o is some wavelength, $\lambda_1 \leq \lambda_o \leq \lambda_2$.

Stellar magnitudes are defined such that anywhere along the brightness scale, a difference of 5 magnitudes corresponds to a ratio of 100 in brightness, or

$$m_1 - m_2 = 2.5 \log_{10}\left(\frac{B_2}{B_1}\right) \qquad (8)$$

where B here refers to brightness. For a given star, then

$$\begin{aligned} m &= -2.5 \log_{10} B + \text{Constant} \\ &= -2.5 \log_{10} E_T + \text{Constant} \qquad (9) \end{aligned}$$

We can write from equation (7)

$$\log_{10} E_T = 2 \log_{10} R_* - \log_{10} \left[\exp\left(\frac{hc}{\lambda_o k T_*}\right)\right] + \text{Constant}$$
$$= 2 \log_{10} R_* - \frac{0.625}{\lambda_o T_*} + \text{Constant} \qquad (10)$$

and putting equation (10) into equation (9)

$$m = -5 \log_{10} R_* - \frac{1.5625}{\lambda_o T_*} + \text{Constant} \qquad (11)$$

Now, visual radiation centers around 5290 Å, and photographic radiation centers around 4250 Å. If we put these values into equation (11) for λ_o, then the *color index I*, can be written

$$I = m_{\text{phot}} - m_{\text{vis}} = \frac{7228}{T_*} + \text{Constant} \qquad (12)$$

The constant is evaluated as follows: by international agreement, the color index is defined to be zero for type AO stars, whose temperature is known by other means to be about 11 200 K. This gives a value of -0.64 for the constant, and equation (12) becomes

$$I = \frac{7228}{T_*} - 0.64 \qquad (13)$$

Since both m_{phot} and m_{vis} can be measured, the surface temperature of the star T_* can be inferred from equation (13)—with all the proper caveats concerning the assumptions about blackbody radiation, centering of the visual and photographic wavelengths, etc.

The *absolute visual magnitude M* of a star is defined to be the magnitude of the star as seen from a distance of 10 parsecs (1 parsec, D, is 3.083×10^{13} km). Absolute magnitude is defined for both visual and photographic magnitudes.

Let $m_1 = M$, in equation (8), be the absolute visual magnitude. Then

$$B_1 = B_2 \left(\frac{d_*/D}{10}\right)^2 \qquad (14)$$

and substituting this into equation (8)

$$M - m = 2.5 \log_{10} \left(\frac{10}{d_*/D}\right)^2$$
$$= 5 - 5 \log_{10} \left(\frac{d_*}{D}\right) \qquad (15)$$

For the Sun, $m_s = -26.72$, $d_s = 1.496 \times 10^8$ km, and hence $M_s = 4.85$.

Since the magnitude definition, equation (8), applies to absolute as well as visual magnitudes, we can interpret equation (11) as referring to absolute magnitude with, of course, a different constant. If we write equation (11) for a star and for the Sun and subtract to eliminate the constant, then

$$M - M_s = -5 \log_{10} R_* + \frac{1.5625}{\lambda_o T_*} + 5 \log_{10} R_s - \frac{1.5625}{\lambda_o T_s}$$

Evaluate this at 5290 Å and rearrange to obtain

$$\log_{10} \left(\frac{R_*}{R_s}\right) = \frac{5907}{T_*} - 0.2M - 0.01 \qquad (16)$$

We now use equation (15) to eliminate the absolute visual magnitude and write equation (16) as

$$\log_{10} \left(\frac{R_*}{R_s}\right) = \frac{5907}{T_*} - 0.2m + \log_{10} \left(\frac{d_*}{D}\right) - 1.01$$

By again using the known values for the Sun and rearranging terms, we get

$$\log_{10} \left(\frac{R_*}{d_*}\right) = \frac{5907}{T_*} - 0.2m - 8.656 \qquad (17)$$

Finally, it might be somewhat more useful to use the color index rather than the temperature, as this is tabulated in many almanacs for many stars. So, by use of equation (13) we can put equation (17) in the form

$$\log_{10} \left(\frac{R_*}{d_*}\right) = 0.817I - 0.2m - 8.130 \qquad (18)$$

This equation gives us a way of estimating the ratio R_*/d_* for a given star, given its visual magnitude and color index and the assumption that it radiates as a blackbody. The color index and apparent visual magnitude for some 1480 stars are given in the *Astronomical Almanac.*

No pretense is made, of course, that equation (18) will give the actual R_*/d_* ratios very accurately, because of the several simplifying assumptions that went into its derivation. It should, though, be at least radiatively consistent with the measured data and hence should perhaps be interpreted as an equivalent or effective value.

Measurements of stellar diameters are rather sparse and imprecise. Measurements of stellar distance are much more accurate and consistent.

Table I gives these parameters for a few stars (Payne-Gaposchkin 1954), whereas table II uses these data to demonstrate the accuracy of equations (17) and (18). By comparing the last two columns of table II—i.e., the "measured" R_*/d_* with the calculated values—it is seen that equation (17) predicts this ratio surprisingly accurately, with only two glaring exceptions: β Centauri and 61 Cygni A. Since the agreement is so good for the other stars, it can probably be considered that either the published R_*/R_s for these stars is considerably uncertain, since the parallax measurements are generally of high quality, or that blackbody radiation does not well characterize the radiation from these particular stars. Since there are 11 instances of good agreement compared with only 2 bad cases, equations (17) and (18) will be used to evaluate R_*/d_* in the remainder of the present work. The paper by Ridgeway et al. (1980) was brought to the author's attention by a reviewer. These writers discuss several modern techniques for measuring the angular diameters of stars (lunar occultation, speckle interferometry, etc.) and give the results of a number of sets of measurements for 22 stars. Kitchin (1984) discusses the theory behind these techniques in great detail. Computations on these stars using equation (18) showed generally the same agreement as presented in table II for Payne-Gaposchkin's data.

Detection of Photons

The number of stellar photons per unit time and area that reach the collector component of an optical instrument in a given wavelength band is given by

$$N_c(T_*) = \left(\frac{R_*}{d_*}\right)^2 \int_{\lambda_1}^{\lambda_2} N_\lambda(T_*)\, d\lambda \quad \frac{\text{photons}}{\text{cm}^2\text{-sec}}$$

and with the same assumptions as made earlier, this can be written

$$N_c(T_*) \approx \left(\frac{R_*}{d_*}\right)^2 \left[\frac{2\pi c}{\lambda_o^4} \frac{1}{\exp\left(\frac{hc}{\lambda_o k T_*}\right) - 1}\right] \times (\lambda_2 - \lambda_1) \quad \frac{\text{photons}}{\text{cm}^2\text{-sec}} \tag{19}$$

If we define

A_c collector area, cm^2

E_c optical efficiency of collector

then the total number of photons that reach the detector of the instrument is

$$N_D(T_*) = A_c E_c \left(\frac{R_*}{d_*}\right)^2 \int_{\lambda_1}^{\lambda_2} \phi(\lambda)\, N_\lambda(T_*)\, d\lambda \quad \frac{\text{photons}}{\text{sec}}$$

$$= A_c E_c\, \phi(\lambda_o)\, N_c(T_*) \tag{20}$$

where $\phi(\lambda_o)$ is some mean value of the spectral response function within the bandpass of the instrument. Since the energy of each photon is hc/λ erg, the total input power reaching the detector is

$$P_{D_i}\,(T_*) = N_D\,(T_*)\,\frac{hc}{\lambda_o} \times 10^{-7} \quad \text{watts} \tag{21a}$$

and the detector output power is

$$P_{D_o}\,(T_*) = P_{D_i}\,(T_*) q \quad \text{watts} \tag{21b}$$

where q is the quantum efficiency of the detector. With λ_o given in microns

$$P_{D_i}\,(T_*) = 1.986 \times 10^{-19}\,\frac{N_D(T_*)}{\lambda_o} \quad \text{watts} \tag{22a}$$

$$P_{D_o}\,(T_*) = 1.986 \times 10^{-19}\,\frac{q N_D(T_*)}{\lambda_o} \quad \text{watts} \tag{22b}$$

The detector output current is

$$i_D(T_*) = N_D(T_*) q e \quad \text{amperes} \tag{23}$$

where $e = 1.6 \times 10^{-19}$ coulombs, the charge of each electron.

Numercial Results

In order to produce some meaningful numerical results, both the characteristics of a bright star and a realistic optical detector system must be assumed. The 15 visually brightest stars were selected as energy sources. The parameters of these stars needed for the present study are given in table III. Of these stars, Capella, Arcturus, and Aldebaran are classified as giants, whereas Betelgeuse and Antares are super giants. The rest are main sequence stars. The temperature range of 3000 K to 18 000 K encompasses practically all the visible stars and so these 15 stars probably present a reasonable cross section of the stars available for an experiment of the type described earlier. The visual magnitudes and color indices were taken from the 1985 edition of the *Astronomical Almanac.* The effective surface temperatures were computed from equation (13) and the ratio R_*/d_* from equation (18).

The detector channels, bandwidths, and quantum efficiencies assumed in the present study are presented in table IV. It must be properly emphasized that this selection is, at least for the purposes of this paper, completely arbitrary and for illustrative purposes only.

Table V through IX present the numerical data computed from the data of tables III and IV and the analysis tools developed in the present paper.

Table V presents computed values of $N_c(T_*)$ and $N_D(T_*)/A_cE_c$ from equations (19) and (20), respectively, since these two parameters are identical for unit response function. Recall that N_c is the number of photons per unit time and area that reach the collector. This number, is of course, independent of any instrument and is a function only of the properties of the star and of its distance from the Earth. On the other hand, N_D has units of photons/sec and represents the actual number of photons per second impinging on the detector. The quantum efficiency of the detector then determines how many of these photons are detectable and/or are turned into some other measurable quantity which is proportional (one hopes linearly) to N_c.

Tables VI through IX are perhaps of more utility. Table VI shows the detector input power per unit collector area in each of the channels and for each of the 15 selected stars and is computed from equation (22a). Table VII shows the detector output power per unit collector area. Table VIII presents the same data as table VII, but each entry has been divided by the assumed channel NEP (noise equivalent power) for the simulated instrument. Thus, each entry of table VIII is essentially the signal-to-noise ratio per unit collector area of the instrument for the selected channels. Table IX contains the detector output current per unit collector area. It can be seen that even for channels 3 and 4, which have the highest quantum efficiencies, the detector response is marginal at best. Only Sirius and perhaps Canopus are bright enough to yield reasonable detector powers.

Also, it must be realized that these numbers are for radiation detected outside the Earth's atmosphere. For an occultation experiment designed to measure the altitude distribution of trace constituents, the stellar radiation is further attenuated as the star rises or sets with respect to the spacecraft. When viewing the star along a ray whose closest distance from the Earth's surface is near the tropopause (10–12 km), the photon counts (table V) can be further reduced by more than two orders of magnitude, with a corresponding reduction in detector power and signal-to-noise ratio.

Comments

It must once again be emphasized that the numbers shown in tables VI through IX were computed for a hypothetical instrument system.

The author is not an instrument specialist; he is only mildly conversant with the fundamentals of collecting and detecting photons and has essentially no knowledge of the actual performance characteristics nor of the operating problems associated with real detectors. From conversations with such specialists, the figures chosen to define the system characteristics used herein are reasonably close to what might be expected in the specialized literature, but neither the performance characteristics nor the conclusions drawn from their use here should be considered definitive. Consequently, the low detector powers and currents displayed in the tables, which seem disappointingly low to this writer, may not at all dismay an electronic specialist who is working at or near the state of the art in photon detector systems. The use, for example, of photomultipliers in the visible portion of the spectrum, and avalanche or cascade photodiodes in the near infrared, may indeed make the detection and amplification of such low power levels possible and useful. The author thus draws no feasibility conclusions from the tables and leaves their interpretation and utility to those more familiar with operational detection systems. Table V is presented without prejudice; it certainly defines the upper limit in what can and cannot be detected and presents initial design information for the design of a working instrument.

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Table I. Selected Parameters for a Few Stars

Star	m	M	T_*, K	R_*/R_s	d_*/D
β Centauri	0.9	−3.8	21 000	11	0.762
Sirius A	−1.6	1.3	11 200	1.8	.376
Procyon A	.5	3.0	6 500	1.9	.291
α Centauri A	.3	4.7	6 000	1.0	.756
61 Cygni A	5.0	8.4	3 800	.7	.296
Kruger 60 A	9.2	11.2	3 300	.34	.256
Barnard's Star	9.7	13.4	3 100	.16	.543
Arcturus	.2	−.3	4 100	30	.080
Aldebaran	1.1	−.1	3 300	60	.057
β Pegasi	2.6	−1.4	2 900	170	.016
Betelgeuse	.9	−2.9	3 100	290	.017
Antares	1.2	−4.0	3 100	480	.0095
Sirius B	8.4	11.2	7 500	.034	.376

Table II. Measured and Calculated R_*/d_* Values for the Stars of Table I

Star	R_*, km	d_*, km	$(R_*/d_*)_{\text{meas}}$	$(R_*/d_*)_{\text{eq. (17)}}$
β Centauri	7.66×10^6	4.05×10^{13}	1.89×10^{-7}	2.79×10^{-9}
Sirius A	1.25×10^6	8.20×10^{13}	1.52×10^{-8}	1.56×10^{-8}
Procyon A	1.32×10^6	1.06×10^{14}	1.25×10^{-8}	1.42×10^{-8}
α Centauri A	6.96×10^5	4.08×10^{13}	1.71×10^{-8}	1.86×10^{-8}
61 Cygni A	4.87×10^5	1.04×10^{14}	4.68×10^{-9}	7.92×10^{-9}
Kruger 60 A	2.37×10^5	1.20×10^{14}	1.97×10^{-9}	1.97×10^{-9}
Barnard's Star	1.11×10^5	5.68×10^{13}	1.96×10^{-9}	2.04×10^{-9}
Arcturus	2.09×10^7	3.85×10^{14}	5.42×10^{-8}	5.56×10^{-8}
Aldebaran	4.14×10^7	5.41×10^{14}	7.73×10^{-8}	8.20×10^{-8}
β Pegasi	1.18×10^8	1.93×10^{15}	6.12×10^{-8}	7.26×10^{-8}
Betelgeuse	2.02×10^8	1.81×10^{15}	1.11×10^{-7}	1.17×10^{-7}
Antares	3.34×10^8	3.25×10^{15}	1.03×10^{-7}	1.02×10^{-7}
Sirius B	2.32×10^4	8.20×10^{13}	2.83×10^{-10}	2.83×10^{-10}

Table III. Visual Magnitude m, Color Index I, Surface Temperature T_*, Radius/Distance to Earth Ratio R_*/d_* for Sun and 15 Bright Stars Used in Text

Star	m	I	T_*, K	R_*/d_*
Archernar	0.46	−0.16	15058.33	$0.44389474 \times 10^{-8}$
Aldebaran	.85	1.54	3315.60	$.90819687 \times 10^{-7}$
Rigel	.12	−.03	11849.18	$.66296408 \times 10^{-8}$
Capella	.08	.80	5019.44	$.32181034 \times 10^{-7}$
Betelgeuse	.50	1.85	2902.81	$.19118332 \times 10^{-6}$
Canopus	−.72	.15	9149.37	$.13694620 \times 10^{-7}$
Sirius	−1.46	.00	11293.75	$.14521116 \times 10^{-7}$
Procyon	.38	.42	6818.87	$.13713238 \times 10^{-7}$
Spica	.97	−.24	18070.00	$.30193955 \times 10^{-8}$
Hadar	.61	−.23	17629.27	$.36315330 \times 10^{-8}$
Arcturus	−.04	1.23	3865.24	$.76367751 \times 10^{-7}$
Rigel Kent	.33	1.00	4407.32	$.41783037 \times 10^{-7}$
Antares	.96	1.83	2926.32	$.14897384 \times 10^{-6}$
Vega	.03	.00	11293.75	$.73113908 \times 10^{-8}$
Altair	.77	.22	8404.65	$.78657475 \times 10^{-8}$
Sun	−26.72	.55	6073.95	$.46062765 \times 10^{-2}$

Table IV. Midpoints of Detector Channels, Bandwidths, and Quantum Efficiencies Assumed (NEP = 1.4×10^{-14} watts for Each Channel)

Channel	λ_o, μm	$\Delta\lambda$, μm	q, electrons/photon
1	1.0197	0.0196	0.21
2	.9355	.0200	.35
3	.5999	.0145	.76
4	.5250	.0148	.65
5	.4524	.0019	.42
6	.4475	.0032	.41
7	.3846	.0198	.30

Table V. Number of Photons per Unit Time and Area Reaching Collector $N_c(T_*)$

Star	$N_c(T_*)$, photons/cm^2-sec, in channel 1	$N_c(T_*)$, photons/cm^2-sec, in channel 2	$N_c(T_*)$, photons/cm^2-sec, in channel 3	$N_c(T_*)$, photons/cm^2-sec, in channel 4	$N_c(T_*)$, photons/cm^2-sec, in channel 5	$N_c(T_*)$, photons/cm^2-sec, in channel 6	$N_c(T_*)$, photons/cm^2-sec, in channel 7
Achernar	0.4331×10^5	0.5450×10^5	0.1060×10^6	0.1397×10^6	0.2315×10^5	0.3967×10^5	0.3052×10^6
Aldebaran	$.4045 \times 10^6$	$.3954 \times 10^6$	$.1253 \times 10^6$	$.7759 \times 10^5$	$.4791 \times 10^4$	$.7587 \times 10^4$	$.1761 \times 10^5$
Rigel	$.6550 \times 10^5$	$.8115 \times 10^5$	$.1410 \times 10^6$	$.1770 \times 10^6$	$.2749 \times 10^5$	$.4686 \times 10^5$	$.3324 \times 10^6$
Capella	$.2260 \times 10^6$	$.2492 \times 10^6$	$.1849 \times 10^6$	$.1620 \times 10^6$	$.1566 \times 10^5$	$.2569 \times 10^5$	$.1021 \times 10^6$
Betelgeuse	$.9720 \times 10^6$	$.9013 \times 10^6$	$.1982 \times 10^6$	$.1061 \times 10^6$	$.5424 \times 10^4$	$.8462 \times 10^4$	$.1567 \times 10^5$
Canopus	$.1741 \times 10^6$	$.2109 \times 10^6$	$.3097 \times 10^6$	$.3619 \times 10^6$	$.5106 \times 10^5$	$.8637 \times 10^5$	$.5439 \times 10^6$
Sirius	$.2892 \times 10^6$	$.3570 \times 10^6$	$.6034 \times 10^6$	$.7489 \times 10^6$	$.1145 \times 10^6$	$.1950 \times 10^6$	$.1357 \times 10^7$
Procyon	$.9272 \times 10^5$	$.1082 \times 10^6$	$.1211 \times 10^6$	$.1260 \times 10^6$	$.1526 \times 10^5$	$.2550 \times 10^5$	$.1330 \times 10^6$
Spica	$.2629 \times 10^5$	$.3339 \times 10^5$	$.6933 \times 10^5$	$.9398 \times 10^5$	$.1617 \times 10^5$	$.2779 \times 10^5$	$.2241 \times 10^6$
Hadar	$.3670 \times 10^5$	$.4655 \times 10^5$	$.9589 \times 10^5$	$.1295 \times 10^6$	$.2219 \times 10^5$	$.3812 \times 10^5$	$.3056 \times 10^6$
Arcturus	$.5303 \times 10^6$	$.5458 \times 10^6$	$.2482 \times 10^6$	$.1779 \times 10^6$	$.1326 \times 10^5$	$.2132 \times 10^5$	$.6198 \times 10^5$
Rigel Kent	$.2526 \times 10^6$	$.2698 \times 10^6$	$.1598 \times 10^6$	$.1276 \times 10^6$	$.1093 \times 10^5$	$.1777 \times 10^5$	$.6105 \times 10^5$
Antares	$.6139 \times 10^6$	$.5712 \times 10^6$	$.1286 \times 10^6$	$.6947 \times 10^5$	$.3596 \times 10^4$	$.5616 \times 10^4$	$.1055 \times 10^5$
Vega	$.7331 \times 10^5$	$.9049 \times 10^5$	$.1530 \times 10^6$	$.1899 \times 10^6$	$.2903 \times 10^5$	$.4943 \times 10^5$	$.3440 \times 10^6$
Altair	$.4842 \times 10^5$	$.5809 \times 10^5$	$.7969 \times 10^5$	$.9043 \times 10^5$	$.1227 \times 10^5$	$.2070 \times 10^5$	$.1242 \times 10^6$
Sun	$.7861 \times 10^{16}$	$.9001 \times 10^{16}$	$.8781 \times 10^{16}$	$.8624 \times 10^{16}$	$.9676 \times 10^{15}$	$.1607 \times 10^{16}$	$.7642 \times 10^{16}$

Table VI. Detector Input Power per Unit Collector Area $P_{D_c}(T_*)/A_cE_c$

Star	$P_{D_c}(T_*)/A_cE_c$, watts/cm^2, in channel 1	$P_{D_c}(T_*)/A_cE_c$, watts/cm^2, in channel 2	$P_{D_c}(T_*)/A_cE_c$, watts/cm^2, in channel 3	$P_{D_c}(T_*)/A_cE_c$, watts/cm^2, in channel 4	$P_{D_c}(T_*)/A_cE_c$, watts/cm^2, in channel 5	$P_{D_c}(T_*)/A_cE_c$, watts/cm^2, in channel 6	$P_{D_c}(T_*)/A_cE_c$, watts/cm^2, in channel 7
Achernar	0.8436×10^{-14}	0.1157×10^{-13}	0.3509×10^{-13}	0.5284×10^{-13}	0.1016×10^{-13}	0.1760×10^{-13}	0.1576×10^{-12}
Aldebaran	$.7878 \times 10^{-13}$	$.8393 \times 10^{-13}$	$.4147 \times 10^{-13}$	$.2935 \times 10^{-13}$	$.2103 \times 10^{-14}$	$.3367 \times 10^{-14}$	$.9091 \times 10^{-14}$
Rigel	$.1276 \times 10^{-13}$	$.1723 \times 10^{-13}$	$.4666 \times 10^{-13}$	$.6695 \times 10^{-13}$	$.1207 \times 10^{-13}$	$.2080 \times 10^{-13}$	$.1717 \times 10^{-12}$
Capella	$.4402 \times 10^{-13}$	$.5290 \times 10^{-13}$	$.6120 \times 10^{-13}$	$.6127 \times 10^{-13}$	$.6873 \times 10^{-14}$	$.1140 \times 10^{-13}$	$.5270 \times 10^{-13}$
Betelgeuse	$.1893 \times 10^{-12}$	$.1913 \times 10^{-12}$	$.6563 \times 10^{-13}$	$.4012 \times 10^{-13}$	$.2381 \times 10^{-14}$	$.3755 \times 10^{-14}$	$.8092 \times 10^{-14}$
Canopus	$.3391 \times 10^{-13}$	$.4476 \times 10^{-13}$	$.1025 \times 10^{-12}$	$.1369 \times 10^{-12}$	$.2242 \times 10^{-13}$	$.3833 \times 10^{-13}$	$.2809 \times 10^{-12}$
Sirius	$.5632 \times 10^{-13}$	$.7578 \times 10^{-13}$	$.1998 \times 10^{-12}$	$.2833 \times 10^{-12}$	$.5028 \times 10^{-13}$	$.8653 \times 10^{-13}$	$.7006 \times 10^{-12}$
Procyon	$.1806 \times 10^{-13}$	$.2297 \times 10^{-13}$	$.4009 \times 10^{-13}$	$.4768 \times 10^{-13}$	$.6699 \times 10^{-14}$	$.1132 \times 10^{-13}$	$.6870 \times 10^{-13}$
Spica	$.5121 \times 10^{-14}$	$.7088 \times 10^{-14}$	$.2295 \times 10^{-13}$	$.3555 \times 10^{-13}$	$.7099 \times 10^{-14}$	$.1233 \times 10^{-13}$	$.1157 \times 10^{-12}$
Hadar	$.7147 \times 10^{-14}$	$.9882 \times 10^{-14}$	$.3175 \times 10^{-13}$	$.4900 \times 10^{-13}$	$.9739 \times 10^{-14}$	$.1692 \times 10^{-13}$	$.1578 \times 10^{-12}$
Arcturus	$.1033 \times 10^{-12}$	$.1159 \times 10^{-12}$	$.8216 \times 10^{-13}$	$.6730 \times 10^{-13}$	$.5822 \times 10^{-14}$	$.9461 \times 10^{-14}$	$.3201 \times 10^{-13}$
Rigel Kent	$.4919 \times 10^{-13}$	$.5728 \times 10^{-13}$	$.5290 \times 10^{-13}$	$.4826 \times 10^{-13}$	$.4799 \times 10^{-14}$	$.7886 \times 10^{-14}$	$.3153 \times 10^{-13}$
Antares	$.1196 \times 10^{-12}$	$.1213 \times 10^{-12}$	$.4259 \times 10^{-13}$	$.2628 \times 10^{-13}$	$.1579 \times 10^{-14}$	$.2493 \times 10^{-14}$	$.5449 \times 10^{-14}$
Vega	$.1428 \times 10^{-13}$	$.1921 \times 10^{-13}$	$.5064 \times 10^{-13}$	$.7182 \times 10^{-13}$	$.1275 \times 10^{-13}$	$.2194 \times 10^{-13}$	$.1776 \times 10^{-12}$
Altair	$.9431 \times 10^{-14}$	$.1233 \times 10^{-13}$	$.2638 \times 10^{-13}$	$.3421 \times 10^{-13}$	$.5388 \times 10^{-14}$	$.9185 \times 10^{-14}$	$.6415 \times 10^{-13}$
Sun	$.1531 \times 10^{-2}$	$.1911 \times 10^{-2}$	$.2907 \times 10^{-2}$	$.3262 \times 10^{-2}$	$.4248 \times 10^{-3}$	$.7131 \times 10^{-3}$	$.3946 \times 10^{-2}$

Table VII. Detector Output Power per Unit Collector Area $P_{D_o}(T_*)/A_cE_c$

Star	$P_{D_o}(T_*)/A_cE_c$, watts/cm^2, in channel 1	$P_{D_o}(T_*)/A_cE_c$, watts/cm^2, in channel 2	$P_{D_o}(T_*)/A_cE_c$, watts/cm^2, in channel 3	$P_{D_o}(T_*)/A_cE_c$, watts/cm^2, in channel 4	$P_{D_o}(T_*)/A_cE_c$, watts/cm^2, in channel 5	$P_{D_o}(T_*)/A_cE_c$, watts/cm^2, in channel 6	$P_{D_o}(T_*)/A_cE_c$, watts/cm^2, in channel 7
Achernar	0.1772×10^{-14}	0.4050×10^{-14}	0.2667×10^{-13}	0.3435×10^{-13}	0.4268×10^{-14}	0.7218×10^{-14}	0.4727×10^{-13}
Aldebaran	$.1654 \times 10^{-13}$	$.2938 \times 10^{-13}$	$.3151 \times 10^{-13}$	$.1908 \times 10^{-13}$	$.8833 \times 10^{-15}$	$.1381 \times 10^{-14}$	$.2727 \times 10^{-14}$
Rigel	$.2679 \times 10^{-14}$	$.6030 \times 10^{-14}$	$.3546 \times 10^{-13}$	$.4352 \times 10^{-13}$	$.5068 \times 10^{-14}$	$.8526 \times 10^{-14}$	$.5150 \times 10^{-13}$
Capella	$.9243 \times 10^{-14}$	$.1851 \times 10^{-13}$	$.4651 \times 10^{-13}$	$.3983 \times 10^{-13}$	$.2887 \times 10^{-14}$	$.4675 \times 10^{-14}$	$.1581 \times 10^{-13}$
Betelgeuse	$.3976 \times 10^{-13}$	$.6697 \times 10^{-13}$	$.4988 \times 10^{-13}$	$.2608 \times 10^{-13}$	$.1000 \times 10^{-14}$	$.1540 \times 10^{-14}$	$.2428 \times 10^{-14}$
Canopus	$.7122 \times 10^{-14}$	$.1567 \times 10^{-13}$	$.7792 \times 10^{-13}$	$.8898 \times 10^{-13}$	$.9415 \times 10^{-14}$	$.1572 \times 10^{-13}$	$.8426 \times 10^{-13}$
Sirius	$.1183 \times 10^{-13}$	$.2652 \times 10^{-13}$	$.1518 \times 10^{-12}$	$.1841 \times 10^{-12}$	$.2112 \times 10^{-13}$	$.3548 \times 10^{-13}$	$.2102 \times 10^{-12}$
Procyon	$.3792 \times 10^{-14}$	$.8039 \times 10^{-14}$	$.3047 \times 10^{-13}$	$.3099 \times 10^{-13}$	$.2814 \times 10^{-14}$	$.4640 \times 10^{-14}$	$.2061 \times 10^{-13}$
Spica	$.1075 \times 10^{-14}$	$.2481 \times 10^{-14}$	$.1744 \times 10^{-13}$	$.2311 \times 10^{-13}$	$.2981 \times 10^{-14}$	$.5057 \times 10^{-14}$	$.3472 \times 10^{-13}$
Hadar	$.1501 \times 10^{-14}$	$.3459 \times 10^{-14}$	$.2413 \times 10^{-13}$	$.3185 \times 10^{-13}$	$.4091 \times 10^{-14}$	$.6936 \times 10^{-14}$	$.4734 \times 10^{-13}$
Arcturus	$.2169 \times 10^{-13}$	$.4055 \times 10^{-13}$	$.6244 \times 10^{-13}$	$.4374 \times 10^{-13}$	$.2445 \times 10^{-14}$	$.3879 \times 10^{-14}$	$.9602 \times 10^{-14}$
Rigel Kent	$.1033 \times 10^{-13}$	$.2005 \times 10^{-13}$	$.4020 \times 10^{-13}$	$.3137 \times 10^{-13}$	$.2016 \times 10^{-14}$	$.3233 \times 10^{-14}$	$.9458 \times 10^{-14}$
Antares	$.2511 \times 10^{-13}$	$.4244 \times 10^{-13}$	$.3237 \times 10^{-13}$	$.1708 \times 10^{-13}$	$.6631 \times 10^{-15}$	$.1022 \times 10^{-14}$	$.1635 \times 10^{-14}$
Vega	$.2998 \times 10^{-14}$	$.6724 \times 10^{-14}$	$.3849 \times 10^{-13}$	$.4668 \times 10^{-13}$	$.5353 \times 10^{-14}$	$.8994 \times 10^{-14}$	$.5328 \times 10^{-13}$
Altair	$.1980 \times 10^{-14}$	$.4316 \times 10^{-14}$	$.2005 \times 10^{-13}$	$.2224 \times 10^{-13}$	$.2263 \times 10^{-14}$	$.3766 \times 10^{-14}$	$.1925 \times 10^{-13}$
Sun	$.3215 \times 10^{-3}$	$.6688 \times 10^{-3}$	$.2209 \times 10^{-2}$	$.2121 \times 10^{-2}$	$.1784 \times 10^{-3}$	$.2924 \times 10^{-3}$	$.1184 \times 10^{-2}$

Table VIII. Detector Output Power per Unit Area Divided by Channel NEP (1.4×10^{-14} watts) of Detector $P_{D_o}(T_*)/A_cE_c\mathrm{NEP}$

Star	$P_{D_o}(T_*)/A_cE_c\mathrm{NEP}$, watts/cm^2, in channel 1	$P_{D_o}(T_*)/A_cE_c\mathrm{NEP}$, watts/cm^2, in channel 2	$P_{D_o}(T_*)/A_cE_c\mathrm{NEP}$, watts/cm^2, in channel 3	$P_{D_o}(T_*)/A_cE_c\mathrm{NEP}$, watts/cm^2, in channel 4	$P_{D_o}(T_*)/A_cE_c\mathrm{NEP}$, watts/cm^2, in channel 5	$P_{D_o}(T_*)/A_cE_c\mathrm{NEP}$, watts/cm^2, in channel 6	$P_{D_o}(T_*)/A_cE_c\mathrm{NEP}$, watts/cm^2, in channel 7
Achernar	0.1265×10^{0}	0.2893×10^{0}	0.1905×10^{1}	0.2453×10^{1}	0.3049×10^{0}	0.5156×10^{0}	0.3377×10^{1}
Aldebaran	$.1182 \times 10^{1}$	$.2098 \times 10^{1}$	$.2251 \times 10^{1}$	$.1363 \times 10^{1}$	$.6309 \times 10^{-1}$	$.9861 \times 10^{-1}$	$.1948 \times 10^{0}$
Rigel	$.1914 \times 10^{0}$	$.4307 \times 10^{0}$	$.2533 \times 10^{1}$	$.3108 \times 10^{1}$	$.3620 \times 10^{0}$	$.6090 \times 10^{0}$	$.3678 \times 10^{1}$
Capella	$.6602 \times 10^{0}$	$.1322 \times 10^{1}$	$.3322 \times 10^{1}$	$.2845 \times 10^{1}$	$.2062 \times 10^{0}$	$.3339 \times 10^{0}$	$.1129 \times 10^{1}$
Betelgeuse	$.2840 \times 10^{1}$	$.4784 \times 10^{1}$	$.3563 \times 10^{1}$	$.1863 \times 10^{1}$	$.7143 \times 10^{-1}$	$.1100 \times 10^{0}$	$.1734 \times 10^{0}$
Canopus	$.5087 \times 10^{0}$	$.1119 \times 10^{1}$	$.5566 \times 10^{1}$	$.6355 \times 10^{1}$	$.6725 \times 10^{1}$	$.1123 \times 10^{1}$	$.6018 \times 10^{1}$
Sirius	$.8448 \times 10^{0}$	$.1894 \times 10^{1}$	$.1084 \times 10^{2}$	$.1315 \times 10^{2}$	$.1508 \times 10^{1}$	$.2534 \times 10^{1}$	$.1501 \times 10^{2}$
Procyon	$.2709 \times 10^{0}$	$.5742 \times 10^{0}$	$.2177 \times 10^{1}$	$.2214 \times 10^{1}$	$.2010 \times 10^{0}$	$.3314 \times 10^{0}$	$.1472 \times 10^{1}$
Spica	$.7681 \times 10^{-1}$	$.1772 \times 10^{0}$	$.1246 \times 10^{1}$	$.1651 \times 10^{1}$	$.2130 \times 10^{0}$	$.3612 \times 10^{0}$	$.2480 \times 10^{1}$
Hadar	$.1072 \times 10^{0}$	$.2470 \times 10^{0}$	$.1723 \times 10^{1}$	$.2275 \times 10^{1}$	$.2922 \times 10^{0}$	$.4954 \times 10^{0}$	$.3382 \times 10^{1}$
Arcturus	$.1549 \times 10^{1}$	$.2897 \times 10^{1}$	$.4460 \times 10^{1}$	$.3125 \times 10^{1}$	$.1747 \times 10^{0}$	$.2771 \times 10^{0}$	$.6858 \times 10^{0}$
Rigel Kent	$.7379 \times 10^{0}$	$.1432 \times 10^{1}$	$.2872 \times 10^{1}$	$.2241 \times 10^{1}$	$.1440 \times 10^{0}$	$.2309 \times 10^{0}$	$.6756 \times 10^{0}$
Antares	$.1794 \times 10^{1}$	$.3032 \times 10^{1}$	$.2312 \times 10^{1}$	$.1220 \times 10^{1}$	$.4736 \times 10^{-1}$	$.7300 \times 10^{-1}$	$.1168 \times 10^{0}$
Vega	$.2142 \times 10^{0}$	$.4803 \times 10^{0}$	$.2749 \times 10^{1}$	$.3334 \times 10^{1}$	$.3824 \times 10^{0}$	$.6424 \times 10^{0}$	$.3806 \times 10^{1}$
Altair	$.1415 \times 10^{0}$	$.3083 \times 10^{0}$	$.1432 \times 10^{1}$	$.1588 \times 10^{1}$	$.1616 \times 10^{0}$	$.2690 \times 10^{0}$	$.1375 \times 10^{1}$
Sun	$.2297 \times 10^{11}$	$.4777 \times 10^{11}$	$.1578 \times 10^{12}$	$.1515 \times 10^{12}$	$.1274 \times 10^{11}$	$.2088 \times 10^{11}$	$.8456 \times 10^{11}$

Table IX. Detector Output Current per Unit Collector Area $i_D(T_*)/A_cE_c$

Star	$i_D(T_*)/A_cE_c$, amperes/cm^2, in channel 1	$i_D(T_*)/A_cE_c$, amperes/cm^2, in channel 2	$i_D(T_*)/A_cE_c$, amperes/cm^2, in channel 3	$i_D(T_*)/A_cE_c$, amperes/cm^2, in channel 4	$i_D(T_*)/A_cE_c$, amperes/cm^2, in channel 5	$i_D(T_*)/A_cE_c$, amperes/cm^2, in channel 6	$i_D(T_*)/A_cE_c$, amperes/cm^2, in channel 7
Achernar	0.1455×10^{-14}	0.3052×10^{-14}	0.1289×10^{-13}	0.1453×10^{-13}	0.1556×10^{-14}	0.2602×10^{-14}	0.1465×10^{-13}
Aldebaran	$.1359 \times 10^{-13}$	$.2214 \times 10^{-13}$	$.1523 \times 10^{-13}$	$.8069 \times 10^{-14}$	$.3219 \times 10^{-15}$	$.4977 \times 10^{-15}$	$.8451 \times 10^{-15}$
Rigel	$.2201 \times 10^{-14}$	$.4545 \times 10^{-14}$	$.1714 \times 10^{-13}$	$.1841 \times 10^{-13}$	$.1847 \times 10^{-14}$	$.3074 \times 10^{-14}$	$.1596 \times 10^{-13}$
Capella	$.7593 \times 10^{-14}$	$.1395 \times 10^{-13}$	$.2248 \times 10^{-13}$	$.1684 \times 10^{-13}$	$.1052 \times 10^{-14}$	$.1685 \times 10^{-14}$	$.4899 \times 10^{-14}$
Betelgeuse	$.3266 \times 10^{-13}$	$.5048 \times 10^{-13}$	$.2411 \times 10^{-13}$	$.1103 \times 10^{-13}$	$.3645 \times 10^{-15}$	$.5551 \times 10^{-15}$	$.7522 \times 10^{-15}$
Canopus	$.5851 \times 10^{-14}$	$.1181 \times 10^{-13}$	$.3766 \times 10^{-13}$	$.3763 \times 10^{-13}$	$.3431 \times 10^{-14}$	$.5666 \times 10^{-14}$	$.2611 \times 10^{-13}$
Sirius	$.9716 \times 10^{-14}$	$.1999 \times 10^{-13}$	$.7338 \times 10^{-13}$	$.7788 \times 10^{-13}$	$.7696 \times 10^{-14}$	$.1279 \times 10^{-13}$	$.6512 \times 10^{-13}$
Procyon	$.3115 \times 10^{-14}$	$.6059 \times 10^{-14}$	$.1473 \times 10^{-13}$	$.1311 \times 10^{-13}$	$.1026 \times 10^{-14}$	$.1673 \times 10^{-14}$	$.6386 \times 10^{-14}$
Spica	$.8834 \times 10^{-15}$	$.1870 \times 10^{-14}$	$.8431 \times 10^{-14}$	$.9774 \times 10^{-14}$	$.1087 \times 10^{-14}$	$.1823 \times 10^{-14}$	$.1076 \times 10^{-13}$
Hadar	$.1233 \times 10^{-14}$	$.2607 \times 10^{-14}$	$.1166 \times 10^{-13}$	$.1347 \times 10^{-13}$	$.1491 \times 10^{-14}$	$.2501 \times 10^{-14}$	$.1467 \times 10^{-13}$
Arcturus	$.1782 \times 10^{-13}$	$.3056 \times 10^{-13}$	$.3018 \times 10^{-13}$	$.1850 \times 10^{-13}$	$.8912 \times 10^{-15}$	$.1399 \times 10^{-14}$	$.2975 \times 10^{-14}$
Rigel Kent	$.8486 \times 10^{-14}$	$.1511 \times 10^{-13}$	$.1943 \times 10^{-13}$	$.1327 \times 10^{-13}$	$.7346 \times 10^{-15}$	$.1166 \times 10^{-14}$	$.2931 \times 10^{-14}$
Antares	$.2063 \times 10^{-13}$	$.3199 \times 10^{-13}$	$.1564 \times 10^{-13}$	$.7225 \times 10^{-14}$	$.2417 \times 10^{-15}$	$.3684 \times 10^{-15}$	$.5065 \times 10^{-15}$
Vega	$.2463 \times 10^{-14}$	$.5068 \times 10^{-14}$	$.1860 \times 10^{-13}$	$.1974 \times 10^{-13}$	$.1951 \times 10^{-14}$	$.3243 \times 10^{-14}$	$.1651 \times 10^{-13}$
Altair	$.1627 \times 10^{-14}$	$.3253 \times 10^{-14}$	$.9690 \times 10^{-14}$	$.9405 \times 10^{-14}$	$.8248 \times 10^{-15}$	$.1358 \times 10^{-14}$	$.5963 \times 10^{-14}$
Sun	$.2641 \times 10^{-3}$	$.5041 \times 10^{-3}$	$.1068 \times 10^{-2}$	$.8969 \times 10^{-3}$	$.6502 \times 10^{-4}$	$.1054 \times 10^{-3}$	$.3668 \times 10^{-3}$

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16. Abstract
The feasibility of using stars as radiation sources for Earth atmospheric occultation experiments is investigated. Exoatmospheric photon counts of the order of 10^6 photons/cm^2-sec are realized for the 15 visually brightest stars. Most photon counts appear to be marginally detectable unless photomultiplier or cascade detection devices can be used.

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