ON THE ABSOLUTE ENERGY DISTRIBUTIONS OF THE SUN, OF THE "SOLAR ANALOGS" 16 CYG B, 16 CYG A, VB 64 AND OF VEGA

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1. INTRODUCTION

In 1984 Neckel and Labs (1984) published improved absolute solar radiation data which followed from an absolute calibration of the Fourier-transform-spectra (FTS) obtained by J. Brault at Kitt Peak. Fig. 1 shows two pages of that special solar spectrum atlas which served to derive the diverse published spectral data. The upper spectrum concerns the disk-center, the lower one the disk-averaged intensity. Both spectra are plotted in the same absolute scale (numbers on the left ordinate axis). The right ordinate axis refers to the full disk spectrum only; it yields the solar irradiance at 1 AU. These spectra, which extend from 3300 to 12500 Å and are stored on magnetic tape, allow an easy derivation of any desired spectral data; e. g. of the spectral averages for successive, rectangular passbands (10, 20 or 50 Å wide) or for any arbitrary passbands used by other observers. The maxima in successive passbands can be used to localize the level of the 'continuum' (dashed lines in Fig. 1).

This paper gives first some general information about the internal errors and the overall accuracy of the two solar spectra. Then the solar flux spectrum is compared with the absolute spectral data of the solar analogs. This comparison reveals minor error waves (amplitudes < 1 %) in the spectra of the Sun and Vega. Finally, some remarks are made on the physical parameters of the two solar analogs 16 Cyg A and 16 Cyg B.

2. INTERNAL ERRORS AND OVERALL ACCURACY OF THE SOLAR SPECTRA

The internal accuracy and consistency of the two solar spectra are demonstrated in Figs. 2 and 3. Fig. 2 shows the radiation temperatures which follow from the intensity maxima in successive 20 Å wide spectral bands. For $\lambda > 4000$ Å these temperatures can be well

J.-P. Swings (ed.), Highlights of Astronomy, 863–873.

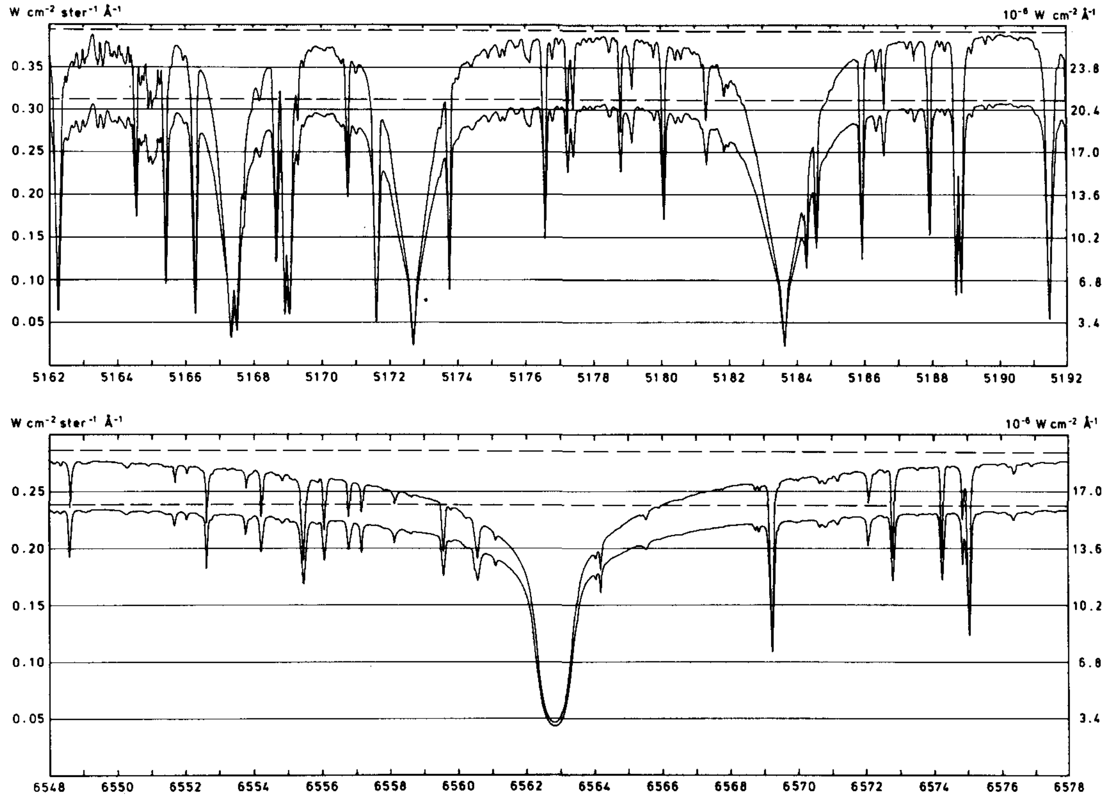

Fig. 1. Two pages of our absolutely scaled solar spectrum atlas for disk-center (above) and disk-averaged (below) intensity.

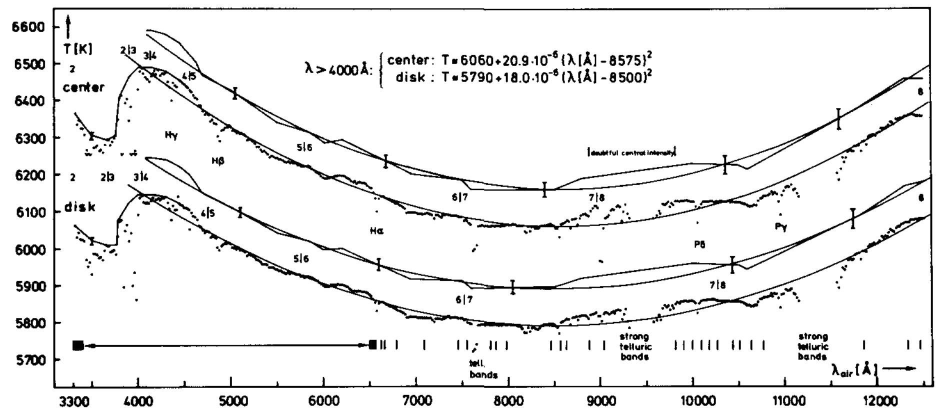

Fig. 2. Radiation temperatures for intensity maxima in successive 20 Å wide spectral bands.

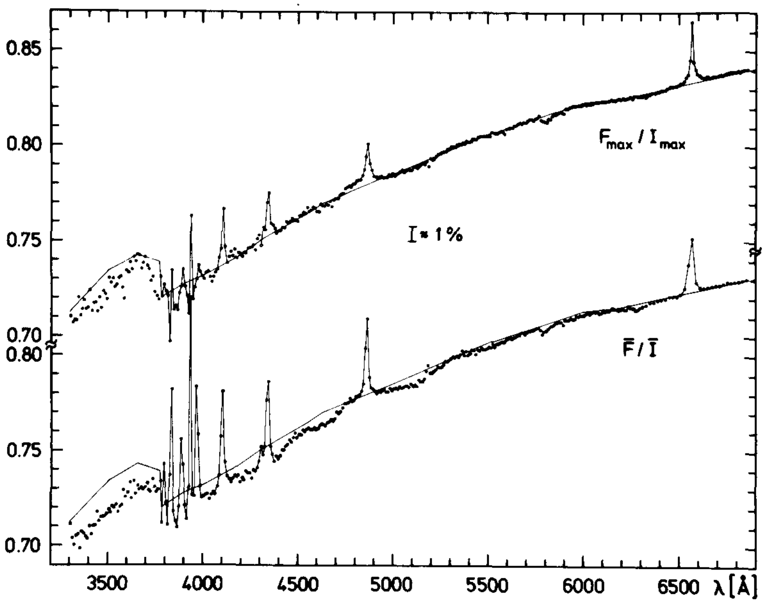

Fig. 3. Ratios of disk-averaged to disk-center intensity for maxima (above) and spectral averages (below) in 10 Å wide spectral bands.

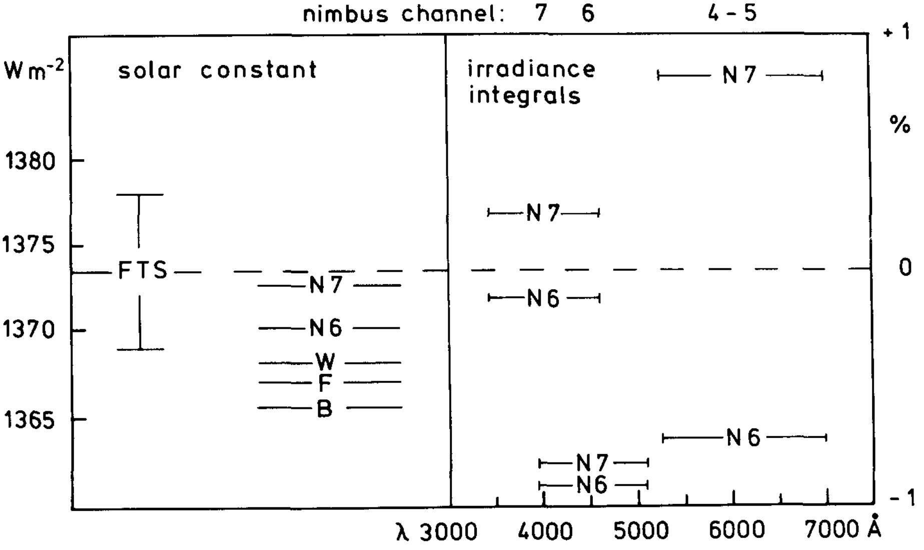

Fig. 4. Comparison of total (left) and partial (right) FTS irradiance integrals with solar constant of Brusa (B), Fröhlich (F), Willson (W) and with Nimbus 7 (N7) results.

approximated by parabolas which have their minima near 8500 Å. A closer approximation is provided by the polygonal curves which are drawn 100 K higher to avoid confusion with the points. The vertical bars denote ± 1 % in intensity.

Fig 3 shows the ratios between disk-averaged and disk-center intensity of the maxima and spectral averages in successive 10 Å wide spectral bands. The scatter below 4500 Å results from genuine differences in the center-to-limb variation of the most effective lines. Such differences also cause the 'Balmer-peaks'. From Figs. 2 and 3 it is obvious that the internal, relative accuracy of any data extracted from the two absolute spectra is about 0.1 %, except of course for regions affected by telluric absorption bands.

Fig. 4. concerns possible systematic errors of the solar flux spectrum. In the left part the total FTS flux integral is compared with recent quotations of the solar constant. The error bar attached to the FTS value marks the uncertainty coming from the absolute data which supplement the FTS spectrum for $\lambda < 3300$ Å and > 12500 Å (taken from other observers). It appears that the FTS-spectrum is in the average too high by about 0.5 %. From this small overall scale error one can conclude that there is also no severe systematic error affecting the intensity distribution. This conclusion is confirmed by irradiance observations made by Shaw and Fröhlich on Mauna Loa and by the Nimbus 6 and 7 broad band results (Fig. 4, right part).

Fig 5 finally compares the absolute solar flux spectrum with the model prediction of Kurucz (1979). The upper part compares the radiation temperatures which correspond to the level of the 'continuum', and the lower part gives the magnitude differences of the FTS spectrum minus the model prediction (a) for the continuum and (b) for the spectral averages inside the passbands chosen by Kurucz. Note that in these comparisons the FTS spectrum still includes all telluric absorption bands.

Part 1 of Fig. 6 shows the magnitude differences of 16 Cyg B minus Sun. The stellar magnitudes, which were taken from Hardorp (1980; band-width $\Delta\lambda = 40$ Å and Taylor (1984; $\Delta\lambda = 49$, 32 or 98 Å, are related here to the energy distribution of Vega provided recently by Hayes (1985). The solar magnitudes were derived from the FTS flux spectrum for exactly the same passbands. The mean, $1/\lambda$-proportional gradient, which corresponds to $\Delta\Theta = 0.009$, has been eliminated.

Figs. 5 to 7 show the magnitude differences between different solar analogs, also in relation the mean, relative gradient. As the standard deviations conform precisely to the observational errors

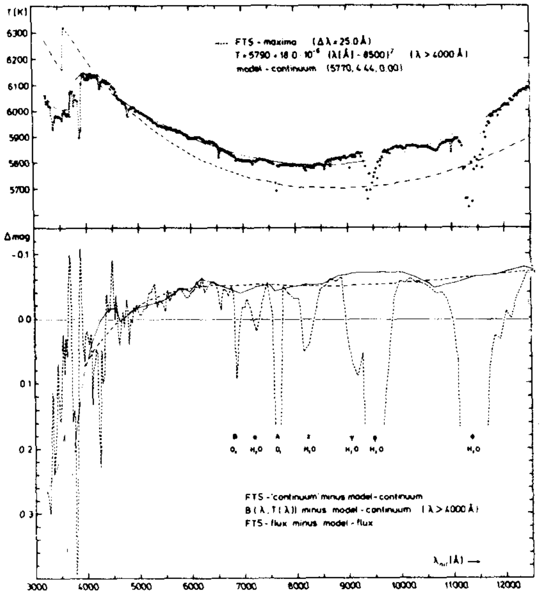

Fig. 5. Comparison of solar flux spectrum with model prediction of Kurucz.

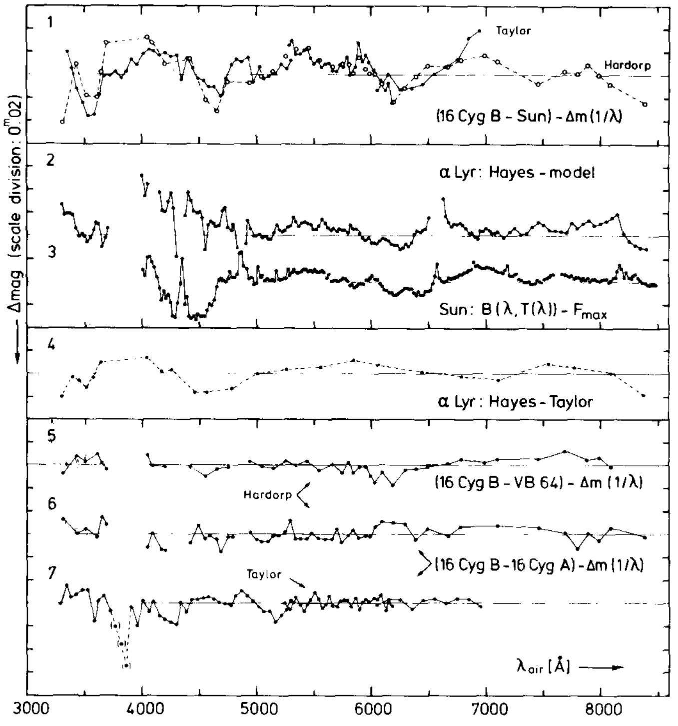

Fig. 6. Comparisons of absolute energy distributions.

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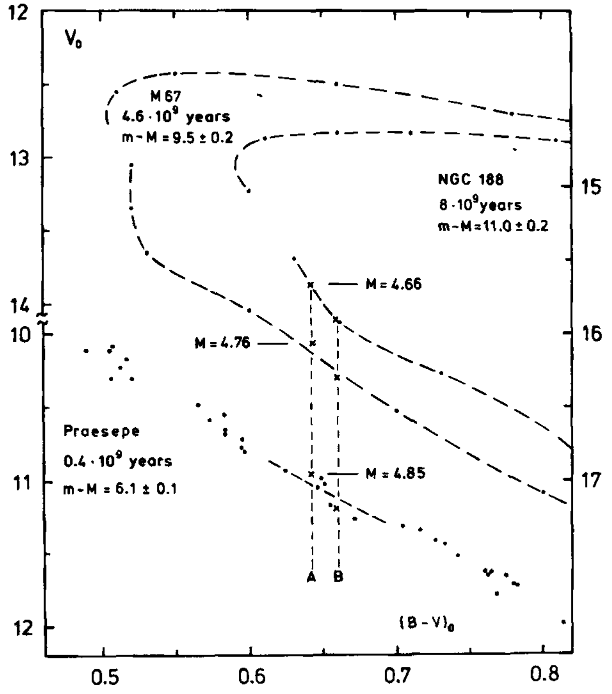

Fig. 7. Absolute magnitudes of 16 Cyg A and B if they are placed on the main sequences of three open clusters with different ages.

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quoted by the observers, there is not much chance for genuine differences in the spectral features (except for the CN bands near 3850 Å). With respect to the handicaps in an absolute photometric comparison between the Sun and stars (apparent size, brightness, day/night) it seems to be a very good result that the standard deviations in Fig. 1 (1.4 %) are just a factor of 2 larger than they are in Figs. 5 - 7 (0.7 %). The reason for the larger standard deviations is obvious; it is the wavy pattern occurring in Fig. 1 for both stellar data sets with remarkable agreement. Figs. 2 to 4 give - presumably - the explanation of this pattern.

Fig. 2 shows the differences between the Vega energy distribution provided by Hayes, which entered into the absolute data of 16 Cyg B, and the Vega model distribution published by Kurucz. Fig. 3 shows for the Sun the differences between those intensities which result from the parabolic approximation of the radiation temperatures and the FTS flux maxima in successive 10 Å wide spectral bands. At least for $\lambda > 5000$ Å the situation seems to be very clear; adding the residuals displayed in Figs. 2 and 3 one gets within observational errors of the stellar data the residuals displayed in Fig. 1. From this fact it is highly probable that for $\lambda > 5000$ Å Figs. 2 and 3 actually display the systematic errors in the observed energy distributions rather than genuine deviations from the adopted reference curves. For $\lambda < 5000$ Å the situation is not quite as clear, but from Fig. 4 one must conclude that in this region a significant contribution to the wavy pattern in Fig. 1 comes from remaining local errors in the energy distribution of Vega. So it is fair to conclude that the spectral distributions of the star minus the Sun differences are actually as smooth as the distributions of the star minus star differences, and that the only significant differences between the Sun and the stars are the relative gradients being proportional to $1/\lambda$.

In Table I the solar analogs are arranged in the order of their gradients relative to the Sun, which is also the order of their colors and of their spectral types (Keenan and Yorka 1985). The stellar colors are adjusted so that their differences correspond exactly to the differences between the gradients, but deviate at most by 0.004 from the values given in the photometric catalogs. These colors and the gradients fix then the colors of the Sun (values without brackets). According to the observed energy distributions the Sun is closer to 16 Cyg A than to 16 Cyg B, which is in agreement with an earlier result of Garrison (1972). However, other results place the Sun closer to 16 Cyg B, a position, which can not be ruled out, since minor systematic errors in the energy distributions of the Sun and Vega must be admitted. Therefore in Table I those values are added in brackets, which result from the assumption that the Sun has the same energy distribution as the Hyades star van Buren 64. Very likely the true

TABLE I

Consistent Spectral Characteristics of the Sun and Solar Analogs

Star	A	Θ_{eff}	T_{eff}	U-B	B-V	Spectral Type
16 Cyg B	279 (102)	0.8814 (0.8757)	5718 (5775)	0.204	0.658	G3 V
VB 64	177 (0)	0.8781 (0.8724)	5740 (5777)	0.200	0.654	G2+ V
Sun		0.8724	5777	0.192 (0.200)	0.646 (0.654)	G2 V
16 Cyg A	-37 (-214)	0.8712 (0.8655)	5785 (5823)	0.192	0.644	G1.5 Vb

$\Delta m = A_o + A_1/\lambda$; $\Delta(\text{color}) = A_1 \times \Delta(1/\lambda)$

colors of the Sun lie somewhere between the bracketed and unbracketed values. Minor variations in the energy distributions of the Sun and/or solar analogs may well contribute to the slight discrepancies. Supposing that the V-magnitude of Vega is 0.03, and that of 16 Cyg B is 6.20, the solar value becomes -26.75; its estimated error is ± 0.025. The Sun's absolute V-magnitude then is 4.85.

4. ON THE PHYSICAL PARAMETERS OF THE 'SOLAR ANALOGS' 16 CYG A AND B

In the sequences of observed energy distributions, of the spectral types and of the effective temperatures deduced from differential spectroscopic studies, the position of the Sun is somewhere between 16 Cyg A and 16 Cyg B. But how close is the agreement of the other parameters, e. g. of the absolute magnitudes?

If the present value of the trigonometric parallax of 16 Cyg (0.039) is correct, then both components A (M_v = 3.92) and B (M_v = 4.16) are significantly brighter than the Sun (M_v = 4.82), which means not only a more advanced phase of evolution, but also luminosities between luminosity classes IV and V. However, results following from the binary nature (same age!) of the two stars indicate that the maximum magnitude difference in temperature between the 'solar analog' and the Sun can not be larger than about 0.4. So, are the color and magnitude differences (A-B) understandable only if both stars are still on the main sequence below the turn-off point (Fig. 7) in an HR diagram?

Fig. 8 displays (as a function of age) the physical parameters (mass M, radius R, gravity g, absolute bolometric magnitude M) of 16 Cyg A and B under the following assumptions: (a) 'A' is slightly hotter and 'B' slightly cooler than the Sun; (b) their difference in log T_{eff} is 0.007; (c) the solar age is 4 billion years; (d) the chemical compositions of the Sun and stars are identical (The values of Y and Z are those given in the insert.). The quoted values of Y, Z and solar age were chosen to avoid a multiple and complex interpolation in the 'Tables of Isochrones' by Ciardullo and Demarque (1977) which served to construct Fig. 8. As only differential effects are to be considered, the use of these, not quite correct values, seems allowable. From the last section in Fig. 8 it is evident that the predicted magnitude difference between the two binary components agrees within the natural scatter (See the Praesepe stars in Fig. 7!) with the observed differences only as long as the age is less than about 9 billion years. This age then sets also the limits for the deviations of the stellar parameters shown in Fig. 8 from the solar values, in particular for the magnitude differences also.

The available orbital motion data also seem to indicate a parallax which is larger than its present trigonometric value. Since the orbital period is of the order of thousands of years, orbital elements are not derivable. But the angular distance and the variation of the distance and position angle with time are rather well established quantities, which allow the derivation of the upper limit of the distance as a function of (a) eccentricity e and (b) difference in radial velocity RV (the mass of the system must be close to $2M_0$, see Fig. 8). The results, which have an accuracy of about 0.5 pc, are shown in Fig. 9. Dash-dotted lines indicate the periastron-distance r_p; the dotted line indicates the orbital period P and the semi-major axis, a.

Assuming p < 200,000 years (e ≈ 0.9) and RV ≈ 1.0 km/s (Bright Star Catalog) one gets for the upper limit of the distance 23 pc. 16

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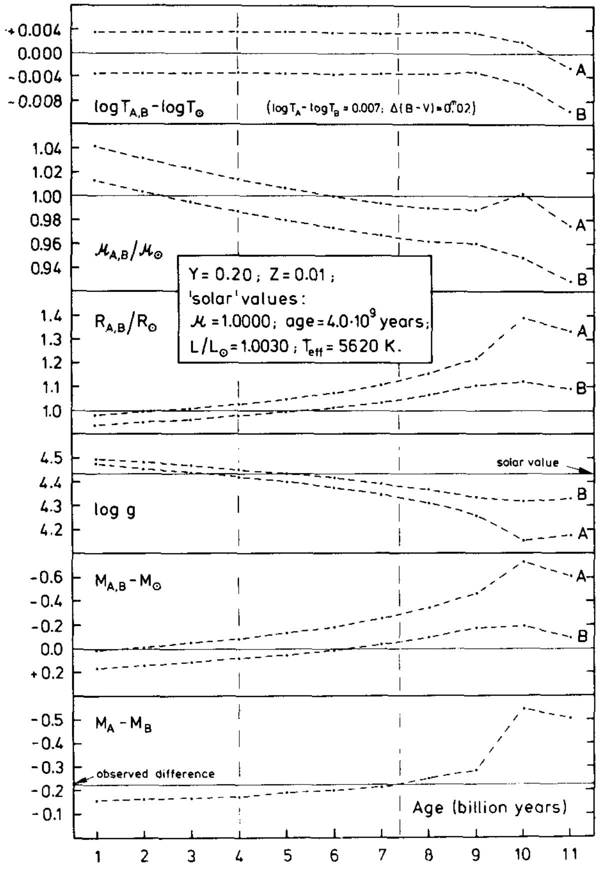

Fig. 8.
Present physical parameters of 16 Cyg A and B as a function of age assuming $T_A - T_{Sun} = T_{Sun} - T_B = 45$ K.

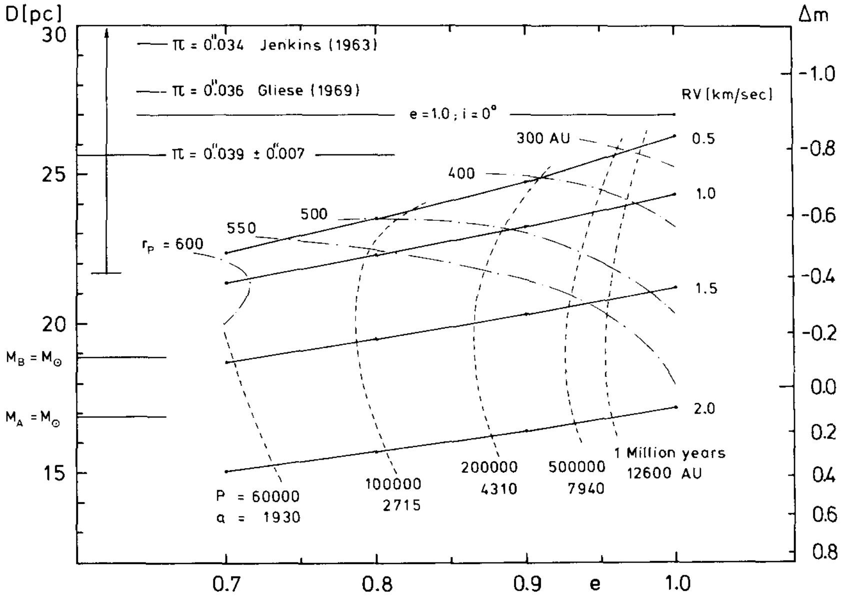

Fig. 9.
Upper limits of the distance of 16 Cyg from orbital motion as a function of eccentricity e and radial velocity RV.

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Cyg B should then be fainter than 4.4 (absolute magnitude), which harmonizes well with the former conclusions.

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