DETERMINING FIELD CORRELATIONS PRODUCED BY STARS FROM THE STUDY OF SPECTRAL CHANGES IN DOUBLE SLIT EXPERIMENT

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(Received 15 December 2000; accepted 29 August 2001)

Abstract. Experiments are performed to determine the coherence properties of wave fields, produced by the broadband stellar sources on the earth surface, from the study of spectral changes produced on interference in the Young's double slit experiment. The spectral degree of coherence obtained experimentally in this study for four bright stars in the wavelength range from 325 nm to 660 nm is in close agreement with the value that is expected theoretically from the known angular diameter of the stars. It is shown that the spectral degree of coherence obtained experimentally by this spectral interferometric technique could be used to determine the angular diameter of stars.

Introduction

Young's interference experiment (Young, 1802) is the basis for Michelson's stellar interferometer for determining the stellar radii and angular separation of double stars (Thomson, Moran and Swenson, 1986; Born and Wolf, 1985; Mandel and Wolf, 1995; Coude du Foresto et al., 1997; Saha, 1999 and references cited there in). In this method the incoming broadband light is made quasi-monochromatic by filtering it and interference fringes are formed. Measuring the visibility is equivalent to measuring the absolute value of the degree of coherence of light incident on the interferometer (Born and Wolf, 1985). From the measurement of visibility of the interference fringes for several separations of the mirrors (called base line lengths), the angular diameter (α) is determined by the position of the first zero in the visibility versus baseline length curve using the formula $\alpha = 1.22\lambda/L$, where λ is the peak wavelength of the quasi-monochromatic radiation and L is the base line length for which the first zero is observed (Michelson, 1890; Michelson and Pease, 1921; Born and Wolf, 1985). This technique forms the basis of interferometric imaging at optical and infrared frequencies and is also employed in radio astronomy. The basic Michelson stellar interferometer measures the coherence factor between two independent pupils for several baseline lengths, which is linked to the Fourier component of the stellar object intensity distribution at the spatial frequencies corresponding to the baseline formed by the pupils. One of the challenges

Astrophysics and Space Science **280:** 209–222, 2002.

of the Michelson stellar interferometer at optical and infrared frequencies is the calibration of the measured coherence factor. The fringe visibility differs from the object visibility because the instrument and the atmosphere have their own interferometric efficiencies, which result in an instrument transfer function T_i and an atmospheric transfer function T_a (Coude du Foresto et al., 1997)

$$\mu = T_i T_a V. \tag{1}$$

An accurate estimate of both transfer functions is required to obtain a good estimate of the visibility. With a carefully designed interferometer, calibration for T_i is not a major problem. The interferometric efficiency of the atmosphere, which is affected by the loss of coherence caused by phase corrugations on each pupil, depends on the instantaneous state of the turbulent wavefronts. Thus T_a is a random variable whose statistics is linked to the evaluation of seeing. There is no way to directly calibrate T_a, that restricts the accuracy of determination of the object visibility. In addition, this method is quite cumbersome and time consuming as it requires determination of the visibility for several baseline lengths and suffers from signal reduction as a large portion of the radiation is lost in making the incident radiation quasi-monochromatic.

In recent years, however, due to many advances that have taken place in stellar interferometry, many interferometers such as the VLTI (Very Large Telescope Interferometer; Mariotti et al., 1998) and the IOTA (Infrared Optical Telescope Array: Carleton et al., 1994) do not necessarily make light quasi-monochromatic. Instead broad band light is used for recombination. But the spatial frequency explored corresponds to an 'effective wavelength'. For this, the interferometer has to be calibrated carefully using frequency stabilized laser interferometers. In addition, determination of coherence fields at many spectral channels (32 spectral channels covering the spectral range from 450 nm to 850 nm), has been exploited by NPOI (Navy Prototype Optical Interferometer: Armstrong *et al.*, 1998; Hajian et al., 1998 and Hutter, 1994) which is a multi channel stellar interferometer. However, the present study deals with the concepts of spectral changes due to the spatial coherence produced on propagation of light for the determination of the spatial coherence over a large spectral range (James and Wolf, 1991) for a two element interferometer.

It has been shown both theoretically (James and Wolf, 1991b, c) and experimentally (Kandpal et al., 1992; Santarsiero and Gori, 1992) that the spatial coherence properties of the broadband radiation incident on a pair of pinholes in the Young's interference experiment modify the spectrum of light in the region of superposition. Such coherence-induced spectral changes have been used for determining the spatial coherence properties of light fields of laboratory sources (Kandpal et al., 1995a and b; James et al., 1995). In these experiments one uses the spectral interference law (Mandel and Wolf, 1976; James and Wolf, 1991b, c) to determine the degree of spectral coherence, over the plane of the Young's double slit, from the study of spectral changes that take place on interference. In many

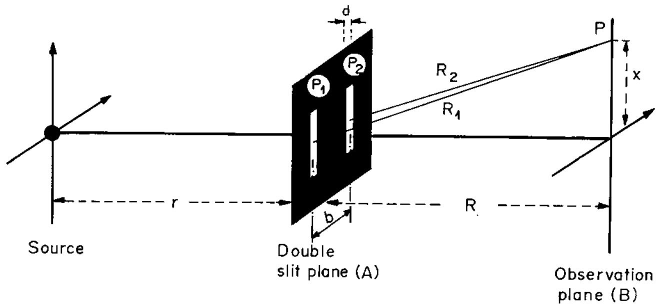

Figure 1. The schematics illustrating the Young's interference setup.

cases of interest, one could make use of the fact that degree of spectral coherence of the field in the far zone of a radiating source obeys the so called *space-frequency equivalence theorem* (James et al., 1995). This principle allows a trade-off between the frequency of the spectrum (ω) and the distance between the pair of points 'd' over which the spectral degree of coherence is determined, since ω and d appear only through the product ωd in the spectral degree of coherence. This implies that a measurement obtained for example by doubling the vector separation from $\mathbf{d}$ to $2\mathbf{d}$ at some frequency ω is equivalent to making the measurement at the original vector separation but at the frequency $2\ \omega$. Some of the laboratory experiments (Kandpal et al., 1995; Kandpal et al., 1995) have shown the application of this technique for determining the angular diameter of the source and angular separation of pair of sources, and thus the feasibility of doing these experiments with stellar sources. The application of this technique for stellar sources as discussed below may offer an advantage over the conventional Michelson stellar interferometer for eliminating the effect of the instrument transfer function T_i and the atmospheric transfer function T_a.

Theory

Let us consider the experimental arrangement shown in Figure 1. The source is assumed to be planar, secondary, quasi-homogenous source which illuminates two identical infinitely long rectangular slits at P_1 and P_2 on an opaque screen A. The width of each slit is d and the separation between the axes of the two slits is b. Let $S(P_1, \omega)$ and $S(P_2, \omega)$ be the spectra of the light on the slits P_1 and P_2, respectively. The spectrum $S(P, \omega)$ measured at a point P (at a distance R_1 and R_2 from P_1 and P_2 respectively) in the plane of observation B parallel to A, can be given by the well-known spectral interference law (Mandel, 1961; Mandel and Wolf, 1995; James and Wolf, 1991a and b),

$$S(P,\omega) = S^{(1)}(P,\omega) + S^{(2)}(P,\omega) + 2\sqrt{S^{(1)}(P,\omega)}\sqrt{S^{(2)}(P,\omega)} \times |\mu(P_1,P_2,\omega)| \cos[\beta(P_1,P_2,\omega) + \omega(R_2 - R_1)/c]. \tag{2}$$

Where $S^{(1)}(P,\omega) = (\omega d^2/2\pi c R) S(P_1,\omega)$ is the spectral density of the light at the P which would be obtained if the slit at P_1 alone is open, has a similar meaning with slit at P_2. $S(P,\omega)$ is the superposed spectrum when both the slits are open, and $\beta(P_1,P_2,\omega)$ denotes the phase of the spectral degree of coherence. The spectral degree of coherence $\mu(P_1,P_2,\omega)$, is given by

$$\mu(P_1,P_2,\omega) \equiv |\mu(P_1,P_2,\omega)| \quad \exp[i\beta(P_1,P_2,\omega)], \tag{3}$$

where $|\mu(P_1,P_2,\omega)|$ is the modulus of the spectral degree of coherence. For on-axis measurements $R_1 = R_2$, and for a centro-symmetric source $\beta(P_1,P_2,\omega)$ may be put either 0 or π in Equation (2), the resulting equation for the modulus of the spectral degree of coherence will be

$$|\mu(P_1,P_2,\omega)| = \frac{S(P,\omega) - S^{(1)}(P,\omega) - S^{(2)}(P,\omega)}{2 \times \sqrt{S^{(1)}(P,\omega) \times S^{(2)}(P,\omega)}} \tag{4}$$

From the measurements of single slit spectra $S^{(1)}(P,\omega)$, $S^{(2)}(P,\omega)$ and the superposed spectrum $S(P,\omega)$ at P, the spectral degree of coherence is obtained by using Equation (4). Equation (4) reveals that for determining the spectral degree of coherence $|\mu(P_1,P_2,\omega)|$, one needs only to measure the relative value of the spectrum. And if the spectral measurements are made under the identical conditions, the common normalization factor will cancel out, and any effect of instrument transfer function may be eliminated.

Experimental Studies

In this paper, we report the application of the spectral interference law for determining field correlation, produced by the stellar sources, which could be utilized for determining the angular diameters of stars. Stars of known angular diameters were chosen and the spectral degree of coherence obtained from the spectral measurements was compared with that obtained by using the van Cittert-Zernike theorem. Since the absorption in the Earth's atmosphere allows only a narrow portion of the spectrum of radiation to reach the Earth, spectral measurements were made in the visible region from 2.35×10^{15} s^{-1} to 5.37×10^{15} s^{-1} (i.e. in the wavelength range from 800 nm to 350 nm) for fixed base line length (i.e. for the fixed separation of Young's slits). Field correlations were determined over the frequency range from 2.35×10^{15} s^{-1} to 5.37×10^{15} s^{-1}.

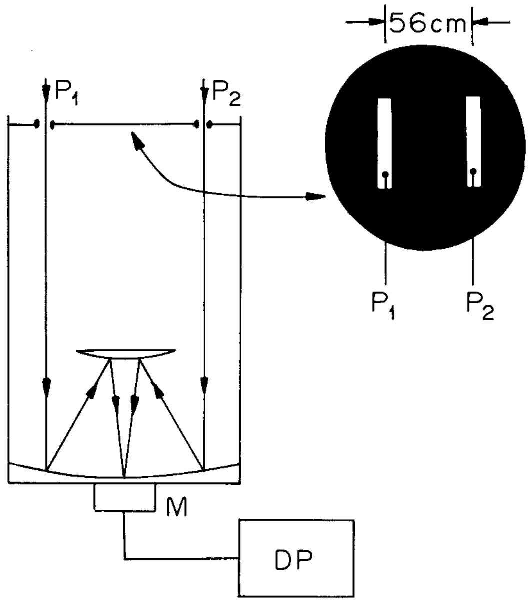

Figure 2. Schematics of 104 cm optical telescope installed at the Uttar Pradesh State Observatory (UPSO), Nainital, and the experimental setup for determining the spectral degree of coherence from spectral measurements. P_1 and P_2 indicate the slits made on a circular disc which was mounted at the top of the telescope, M is the monochromator and DP is the data processor.

The experiments were performed at the Uttar Pradesh State Observatory (UPSO), situated at Manora Peak (longitude 79°27′E, latitude 29°22′ and altitude 1951 m), Nainital, India and a 104 cm optical telescope (Figure 2) made by Carl Zeiss Jena, GmbH, Germany was used. This telescope has f/13 Ritchey-Chretien Cassegrain and f/31 Coude foci. The reflecting optics of the telescope is made up of Rastotherm glass having a coefficient of linear expansion 33.7×10^{-7}/°C. The aluminum coating of mirrors with a protective coating of magnesium fluoride has a reflectivity of 90% at a wavelength of 500 nm. The transmitting optics is made up of fused quartz. The primary mirror of the telescope is a concave hyperboloid having a clear aperture 104 cm and focal ratio f/4. The telescope has two pier equatorial English mounting and has been provided with an instrument rotator. For making spectral measurements, a HR-320 Carl Zeiss Jena monochromator with a holographic grating with 600 l mm^{-1} and having dispersion 5 nm mm^{-1} was used at the f/13 RC-Cassegrain focus of the telescope. A sky field viewing and slit viewing arrangement was also attached before the entrance slit of the monochromator, which allows only 45 arc sec of sky to go through the monochromator. The detector used to record the spectra was a liquid nitrogen cooled 1024 × 1024 Tektronix CCD camera system. The size of a pixel is 24 micron and one pixel covers 0.32 arc second of the sky. All the observations were taken when the sky conditions were suitable for photoelectric photometry and the stars under study were nearly at the zenith.

To verify the theoretical predictions (James and Wolf, 1991a, b, and c) and the laboratory experiments (Kandpal et al., 1995; Kandpal *et al.*, 1995) with the natural (stellar) sources, we chose some of the bright stars of known angular diameters (obtained by other interferometric methods) namely α-Boo (Arcturus), α-Sco (Antares), α-Cma (Sirius) and α-Ori (Betelegues). The two stars α-Boo, α-Sco were particularly chosen during summer months as they were seen nearly at the zenith between 9 p.m. to 1 a.m. The other stars α-CMa and α-Ori were chosen for the study during winter when they were near the zenith. We know that stars are very small compared with their distances from the earth and by using the van Cittert-Zernike theorem, the spatial coherence generated at a pair of spatial points (Young's slits in Figure 1) can be calculated. Assuming the stars to be centro-symmetric circular discs and the slits to be located symmetrically with respect to the normal to the source plane, passing through the center of the source, the spectral degree of coherence of the light incident on the slits at two spatial points P_1 and P_2 separated by a distance b, $\mu(P_1, P_2, \omega)$ may be readily determined by using the reciprocity relations for the field generated by planar quasi-homogeneous source (Carter and Wolf, 1977) and is given as

$$\mu(P_1, P_2, \omega) = \frac{2J_1\left(\frac{\alpha\omega b}{c}\right)}{\left(\frac{\alpha\omega b}{c}\right)}, \tag{5}$$

where J_1 is first order Bessel function, α is the angular semi-diameter of the star, ω is the frequency of the star light and c is the velocity of light in vacuum and b is the base line length. In this study, we have made an implicit assumption that the surface morphology of the star is not dependent on the wavelength of the radiation.

To obtain the spectral degree of coherence experimentally, a double slit was made in the form of two rectangular slits (at P_1 and P_2 as shown in Figure 2, also referred as Young's double slit) of dimensions 80 cm length and 4 cm wide and their axes separated by 56 cm on an aluminum disc of 106 cm diameter and 5 mm thick. This double slit arrangement was mounted at the top of the telescope (Figure 2). The slits were opened and closed from the ground by pulling long strings tied with the slits. After mounting the double slit at the top of the telescope tube, the monochromator was attached with the telescope at the Cassegrain focus. The focused image of α-Boo, with one slit at P_1 open and the other at P_2 closed and vice versa and also with both the slits open, was brought exactly at the entrance aperture of the monochromator. After the fine adjustment, the liquid nitrogen cooled CCD array detector was attached with the monochromator such that the exit slit of the monochromator was exactly at the front surface of the detector. The output of the detector was connected to a computer for data acquisition and analysis. The spectral degree of coherence $\mu(P_1, P_2, \omega)$ was obtained by probing the spectral changes that occur on interference of the light from the two sources at P_1 and P_2.

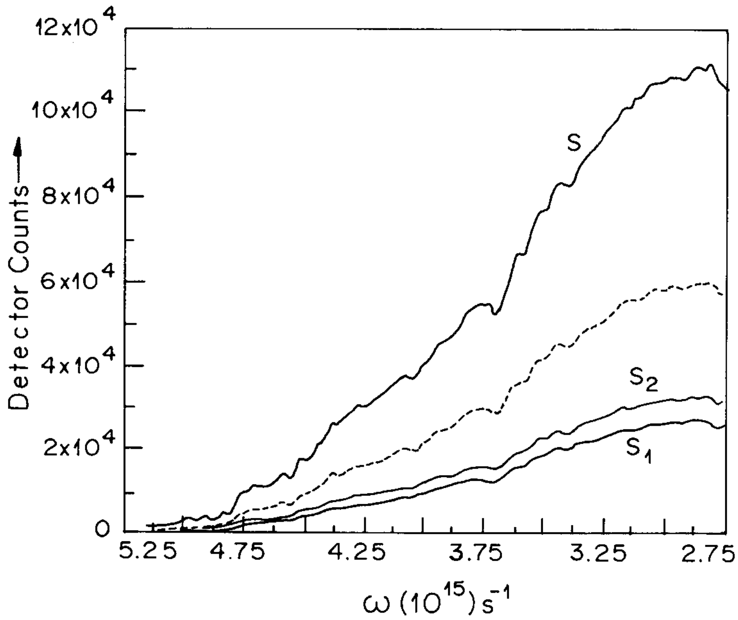

Figure 3. Spectrum of α-Boo star at an on-axis observation point at the focus of the telescope. Curves S_1 and S_2 are the recorded spectra when slit P_1 is open and P_2 closed and slit P_2 is open and P_1 closed respectively. Curve S is the recorded spectrum when both the slits at P_1 and P_2 open. Dotted line curve is the summation of the curves S_1 and S_2.

The single slit spectra and the superposed spectra of the light from the stars α-Boo, and α-Sco were taken for on-axis point of observation. These spectra were measured from 360 nm to 660 nm. It may be noted that α-Sco has companion β-Sco but our viewing condition restricts field size to 45 arc sec, which allows light from α-Sco only to enter the spectrograph. The integration time was kept 2 s for recording one spectrum. Measurements were repeated for integration time varying from 35 ms to 10 s. No distinguishable change in the spectrum was observed, which indicates that atmospheric turbulence effect on the spectra was negligible. As a result of atmospheric fluctuations, the path difference $(\omega/c)(R_2 - R_1)$ may not be exactly zero and the measured superposed spectrum would show modulations due to $\cos\{(\omega/c)(R_2 - R_1)\}$ factor (see Equation 2). However, we did not observe any modulations in the superposed spectrum and therefore we have used Equation (4) for determining the degree of spectral coherence.

These measurements were taken for eight nights during summer months when the star under study was near zenith. The superposed spectrum in each measurement was found to be different from the corresponding single slit spectrum. However, the single slit spectra on all observing nights were almost similar and the superposed spectra were also similar in repeat measurements. These spectra for the two sets of measurements made at different times of a season were found to be

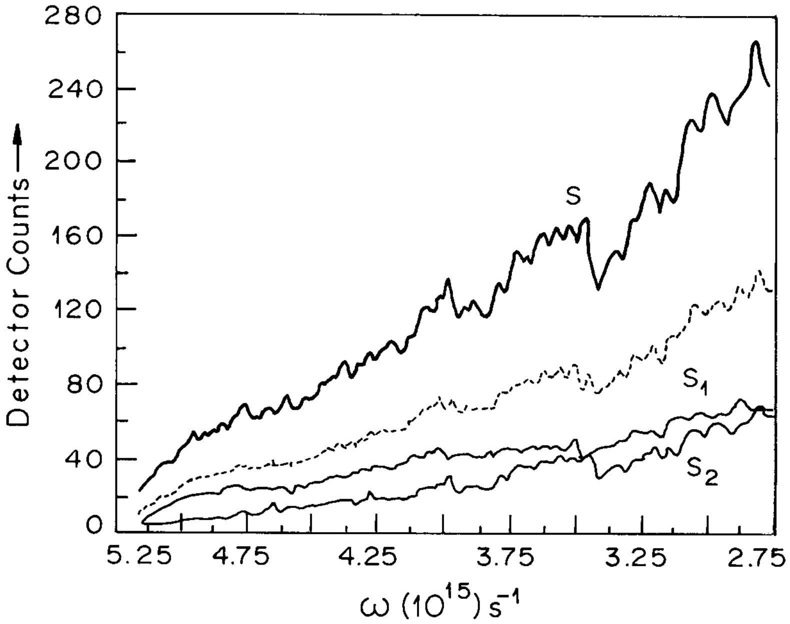

Figure 4. Spectrum of α-Sco star at an on-axis observation point at the focus of the telescope. Curves S_1 and S_2 are the recorded spectra when slit P_1 is open and P_2 closed and slit P_2 is open and P_1 closed respectively Curve S is the recorded spectrum when both the slits at P_1 and P_2 open. Dotted line curve is the summation of the curves S_1 and S_2.

identical. No change in the spectra was found for measurements made over integration time varying from 1 s to 5 s. Sample spectra for α-Boo and α-Sco (single slit spectrum and the superposed spectrum) are shown in Figures 3 and 4 respectively. These observations suggest that the influence of the changing atmosphere is smaller in spectral measurements than its influence in visibility measurements of interference fringes with quasi-monochromatic sources. In the later case one needs to restrict the integration time to about 35 ms if intensity interference fringes are to be observed without smearing.

The average value of the spectral degree of coherence is obtained using Equation (4) from repeat measurements of single slit and superposed spectrum for the chosen star. Since the spectral measurements were made under the identical conditions of the telescope, monochromator and the detector system it is sufficient to determine the relative value of the spectrum as the common normalization factor cancels out. The average value of the spectral degree of coherence obtained using Equation (4) from repeat spectral measurements in the spectral range from 360 nm to 660 nm for the star α-Boo is shown by solid dots and the standard deviations are shown as error bars in Figure 5.

The theoretically calculated value of the spectral degree of coherence obtained using Equation (5) from the known angular diameter of the star α-Boo, namely

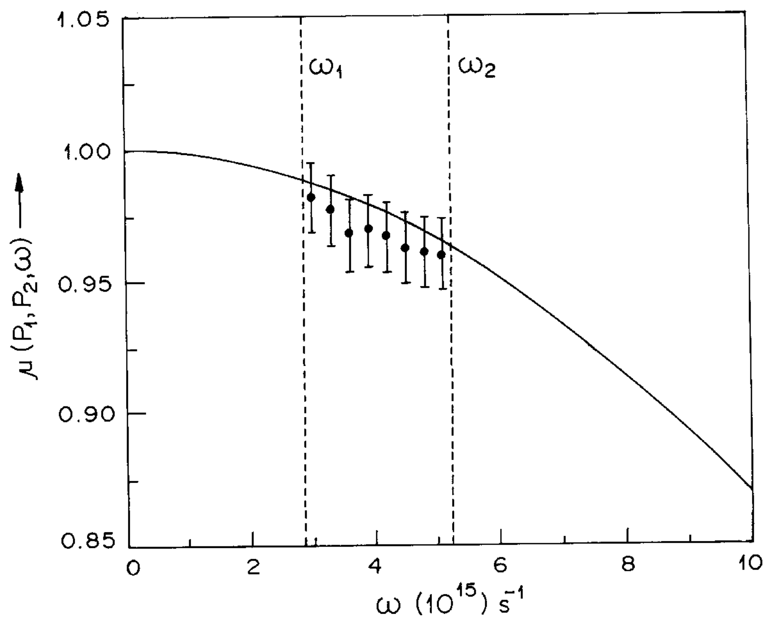

Figure 5. Variation of spectral degree of coherence with frequency. Solid dots with error bars are obtained using Equation (4) from large number of measurements of the spectral distributions of α-Boo. The spectral distribution of α-Boo is shown in Figure 3. Solid curve is the theoretical expected curve using experimental parameters $2\alpha = 23.1 \times 10^{-3}$ arc second and $b = 56$ cm in Equation (5). In the figure $\omega_1 = 2.86 \times 10^{15}$ s^{-1} corresponds to $\lambda = 660$ nm and $\omega_2 = 5.24 \times 10^{15}$ s^{-1} corresponds to $\lambda = 360$ nm.

23.1×10^{-3} arc second and $b = 56$ cm is shown by solid line in the Figure 5 and is in agreement with experimental results within experimental errors. Spectroscopic studies made with α-Sco also reveal that the spectral degree of coherence obtained from the spectral changes that occur due to interference and that expected theoretically from the known parameters of the star (namely angular diameter 42.5×10^{-3} arc second) match closely within experimental errors and limitations. The experimental and the theoretical values of the spectral degree of coherence for α-Sco, obtained by using Equations (4) and (5) respectively, are shown in Figure 6.

Similar experimental measurements were done for the stars α-CMa and α-Ori during winter months when these were seen near zenith. The spectra were measured from 325 nm to 590 nm and the integration time in this case too was kept 2 s. The spectroscopic measurements were repeated several times for the both the stars for two nights. Results of spectral measurements for α-CMa and α-Ori were similar to those obtained for α-Boo and α-Sco.

The spectral degrees of coherence for the star α-CMa and α-Ori were calculated by putting the values of the superposed spectrum and the single slit spectrum in Equation (4). The average value of the spectral degree of coherence from repeat measurements for these stars (α-CMa and α-Ori) are shown by solid dots and the

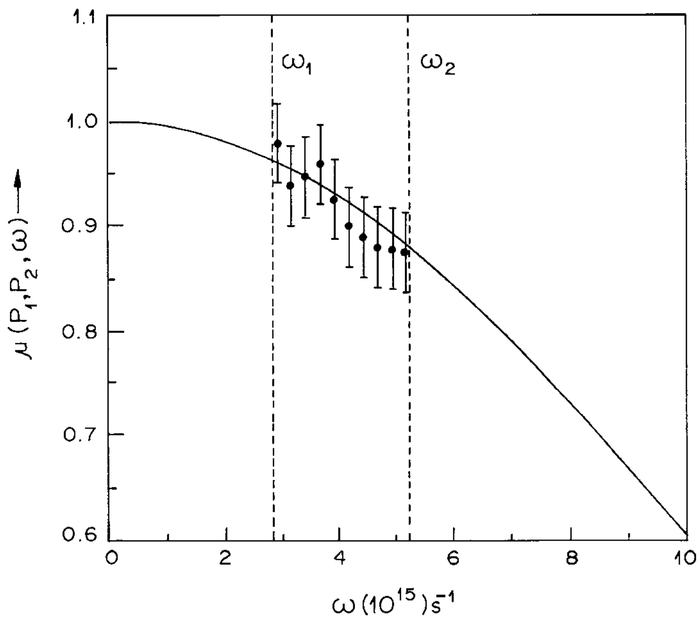

Figure 6. Variation of spectral degree of coherence with frequency. Solid dots with error bars are obtained using Equation (4) from large number of measurements of the spectral distributions of α-Sco. The spectral distribution of α-Sco is shown in Figure 4. The solid curve is the theoretical expected curve using experimental parameters $2\alpha = 42.5 \times 10^{-3}$ arc second and $b = 56$ cm in Equation (5). In the figure $\omega_1 = 2.86 \times 10^{15}\ s^{-1}$ corresponds to $\lambda = 660$ nm and $\omega_2 = 5.24 \times 10^{15}$ s^{-1} corresponds to $\lambda = 360$ nm.

standard deviations are shown as error bars in Figures 7 and 8 respectively. The theoretically calculated value of the spectral degree of coherence in the spectral range from 325 nm to 590 nm obtained using Equation (5) from the known angular diameter of the star, α-CMa namely 6.3×10^{-3} arc second and $b = 56$ cm is shown by solid line in Figure 7 and is in agreement with experimental results within experimental errors. Spectroscopic studies made with α-Ori also reveal that the spectral degree of coherence obtained from the spectral changes that occur due to interference and that expected theoretically from the known parameters of the star (namely angular diameter 47×10^{-3} arc second) match closely within experimental errors and limitations. The experimental and the theoretical values of the spectral degree of coherence for α-Ori, obtained by using Equations (4) and (5) respectively, are shown in Figure 8.

Discussions

The values of the spectral coherence lengths at a mean wavelength of 500 nm of the radiation emitted by the stars α-Boo, α-Sco, α-CMa and α-Ori are approximately

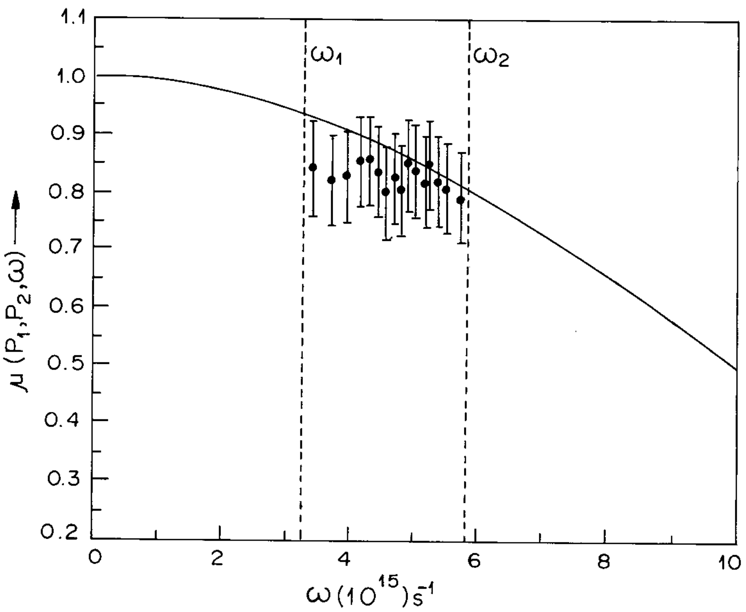

Figure 7. Variation of spectral degree of coherence with frequency. Solid dots with error bars are obtained using Equation (4) from large number of measurements of the spectral distributions of α-CMa. The solid curve is the theoretical expected curve using experimental parameters $2\alpha = 6.3 \times 10^{-3}$ arc second and $b = 56$ cm in Equation (5). In the figure $\omega_1 = 3.19 \times 10^{15}$ s^{-1} corresponds to $\lambda = 590$ nm and $\omega_2 = 5.79 \times 10^{15}$ s^{-1} corresponds to $\lambda = 325$ nm.

5.04 m, 2.74 m, 20 m and 2.74 m, respectively. Since the separation of Young's slits was 56 cm in our experimental setup, the spectral degree of coherence would not vary significantly over the plane of the double slit in the wavelength range from 360 nm to 660 nm. For getting the zero in the spectral degree of coherence, this was one of the constraints in our experimental setup because of the diameter of the telescope. However, we have found experimentally that the spectral degree of coherence produced by α-Sco and α-Ori at the plane of Young's double slit varies more rapidly compared to the spectral degree of coherence produced by α-Boo and that of α-CMa. This is consistent with the theoretically expected value of the spectral degree of coherence for these stars. In these measurements the experimental errors are somewhat large. They may be due to atmospheric turbulence effects since measurements of single slit spectra and superposed spectrum were made at different times. If a system based on the concepts developed by Coude du Foresto et al. (1997) is used for simultaneous measurements of single slit spectra and superposed spectrum, it might reduce the uncertainty in the determination of spectral degree of coherence. Other factors responsible for measurement uncertainty may be due to. (i) the focused light not exactly at the entrance slit of the monochromator, (ii)

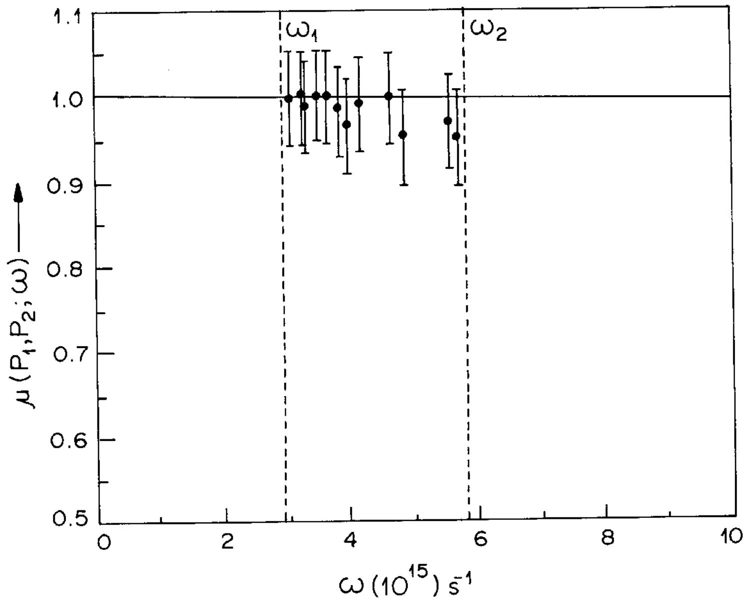

Figure 8. Variation of spectral degree of coherence with frequency. Solid dots with error bars are obtained using Equation (4) from large number of measurements of the spectral distributions of α-Ori. The Solid curve is the theoretical expected curve using experimental parameters $2\alpha = 47 \times 10^{-3}$ arc second and $b = 56$ cm in Equation (5). In the figure $\omega_1 = 3.19 \times 10^{15}$ s^{-1} corresponds to $\lambda = 590$ nm and $\omega_2 = 5.79 \times 10^{15}$ s^{-1} corresponds to $\lambda = 325$ nm.

unsymmetrical placement of the slits with respect to the normal to the source plane (iii) the noise in the electronic system (iv) the non-linearity of the detector etc.

As has been discussed earlier that the instrument and the atmosphere have their own interferometric efficiencies resulting in an instrument transfer function and atmospheric transfer function. In the determination of $|\mu(P_1, P_2, \omega)|$ as one needs only to measure the relative value of the spectrum and if the spectral measurements are made under the identical conditions of the telescope, monochromator and the other instruments, the common normalization factor will cancel out in $|\mu(P_1, P_2, \omega)|$ which is basically a ratio measurement.

It is well known that atmospheric fluctuations smear the visibility of the intensity interference fringes due to phase screen formed by the atmosphere. The distortion in the wave front of the light field caused by the fluctuations in the atmosphere affects the fringe visibility. It has been shown that the spectra of light fields would be affected by scattering through the propagating media if the frequency of the randomness of the fluctuations of the media is of the order of the fluctuations of the light fields (James and Wolf, 1990, 1994; James, Savedoff and Wolf, 1990). Since the frequency of the fluctuations in the earth atmosphere is very low compared to the frequency of the fluctuations of the light fields, the spectrum of the light during its propagation would not be affected. The results of the experimental study conducted by us are consistent with these predictions as the spectra remained almost identical despite a large change in integration time (35 ms to 10 s) in the spectral data collection.

Conclusions

The spectral degree of coherence obtained experimentally (within experimental errors) in this study for four bright stars in the wavelength range from 325 nm to 660 nm is in close agreement with the value that is expected theoretically from the known angular diameter of the stars. These results show that this new spectral interferometric technique being simple and quick, might find an edge over the existing interferometric methods. The spectral degree of coherence obtained from spectral interferometric technique could be used for determining angular diameter of stars. Though the range of optical frequencies available on the Earth's surface is limited, but one can determine the angular diameter of stellar sources to a modest accuracy. Future observations with a collecting system of two identical telescopes, to get varying base line length of a few meters, along with suitable fibre optics for simultaneous measurements of single slit spectra and superposed spectrum are likely to offer better opportunities for finding the angular diameters of the faint and distant stars.

Acknowledgements

The authors are thankful to the Director, National Physical Laboratory, New Delhi, India for permission to publish this paper. The authors DSM and ESRG are thankful to the Council of Scientific and Industrial Research (CSIR) New Delhi, India for financial support.

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