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Interferometry and Spectrophotometry of Solar Type Binary Stars

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"Each time I was in a problem, or I faced the dark side of this life...
Each time I was in happiness, or I faced the shiny side of this life...
There was a hidden strength, either from inside myself or through my relatives and friends, pushing me forward.
To the Almighty and holder of that strength,
and
To all those whom I felt that strength through,
I dedicate this work. "

Mashhoor

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Introduction

Actuality

The correlation between spatial locations, dynamical characteristics, ages and metallicities of the main sequence stars is the key for the understanding of the chemical and dynamical evolution of our Galaxy. But even in the vicinity of the sun (d $<$ 50 pc), this correlation still remains hardly vague because of the big uncertainties in the determination of the main stellar parameters (Andersen J. 1991,1998).

Nearby stellar populations are occupied mainly by dwarfs of F, G, K and M spectral types, with metallicities in the range -1.0 $<$ [Me/H] $<$ +0.3. More than 50% of these stars are members of binary and multiple systems(Abt & Levy 1976; Duquennoy & Mayor 1991). For such unrecognized systems, natural uncertainties in the determination of photometrical parallaxes, masses, ages and metallicities might be the main reasons of scattering of the points in the known statistical dependencies (Nordström et al. 1999).

Most of the unrecognized binary and multiple systems are of the young rapidly rotating main sequence F-stars. For which, the radial velocities as well as the existence of a companion is difficult to define by spectroscopy. Also young F-dwarfs, which have not had enough time to leave their forming regions, are quite important for metallicity distribution studies. Generally, such problem can be solve only by means of interferometric and spectrophotometric observations.

Unresolved binaries, for which separate determination of spectral and photometrical properties is impossible, are usually excluded from observational programs and statistical analysis of normal stars. But big part of the unrecognized multiple systems can significantly change dependencies such as mass-luminosity, mass-radius, age-luminosity and scale of effective temperatures. Moreover, statistical properties are directly connected with the stars formation, but accuracy in such relationships is not enough for the investigation of the modern theories of stellar formation and evolution.

So, the complex study of binary and multiple systems by different observational methods have in principal significant importance in the determination of the main features of the different types of stellar populations in the Galaxy.

Binary systems give a unique possibility for the direct determination of the complete set of stellar parameters without depending on any statistical relations. Such possibility, however, can only be applied for objects having a possibility to be observe by means of different observational methods.

Progress in observational techniques and data processing have greatly increased the number of binary and multiple systems available to the complex studies. This provides a possibility of revision of the statistical dependencies on the basis of the direct determination of the complete set of fundamental parameters of the components of these systems. These parameters are defined by parallax measurements, interferometry, radial velocity measurements and spectrophotometry.

Hipparcos catalogue (ESA, 1997) is the most full and reliable source of the information about stellar parallaxes - it contains more than 20000 parallax measurements for nearby stars with distance estimation errors better than 10%. However, binary systems parallax determinations were distorted by their orbital motions, the reason why their real accuracy was much lower than those of single stars. So, Speckle-Interferometry remains the main method of determination of binary stars' visual orbits.

In the Fourth Catalogue of Interferometric Measurements of Binary Stars (http://ad/-usno.navy.mil/wds/int4.html), one can find more than 28600 observations, made at different telescopes. In comparison with the classical methods of studying visual binary stars, interferometry enables the measurements of less separated systems with higher accuracy.

The only mission which has more observations than speckle-interferometry is Hipparcos, but it had a lower accuracy, larger limited separation and insufficient mission life-time for reconstructing of the orbits. Concerning long-base interferometry, its advantages of high precision and resolution were restricted by low sensitivity and small number of observations.

Speckle-interferometry also enables us to measure the magnitude differences. But due to methodical problems, high-precision Δm speckle-measurements were not possible until recent time (Worley et al. 2001). So, such measurements have been obtained only episodically by means of different algorithms in random photometrical bands. The precision of these measurements was not better than $0\overset{m}{.}2$, and it is even difficult to estimate their reliability.

Differential photometry of binary stars was made by HIPPARCOS, but for pairs as faint as $10^m - 12^m$ with separation less than $0\overset{''}{.}3$, errors were comparable with the measured values. The method of Δm definition carried at SAO RAS via speckle-interferometry provides magnitude differences measurements for systems brighter than 13^m with $\Delta m \leq 4^m$ and precision about $0\overset{m}{.}05$. For pairs wider than $0\overset{''}{.}3$, interferometric errors are comparable to those of HIPPARCOS, but for closer pairs they are much smaller (Balega et al. 2002).

Interferometric binary orbits combination with the components' radial velocities provides direct masses and parallaxes estimations with precision much better than any other method.

Systematic monitoring of several thousands of nearby solar type stars is carrying out with the velocity measuring device CORAVEL in both north and south hemispheres (Duquennoy & Mayor 1991; Halbwachs et al. 2003). Significant part of these objects (pairs with orbital periods from several hundreds of days till decades) are the candidates for speckle-interferometric measurements on the largest telescopes.

The combination of interferometric Δm results with the spectrophotometric data allows to build individual model atmospheres for each component of a binary system. The Result of such measurements is the determination of the statistical dependencies for stars of different types with accuracy enough for theoretical researches.

Thereby, the actuality of the dissertation's task raised from the necessity and opportunity to improve statistical dependencies for F, G and K stars, a knowledge will improve - in its turn - the understanding of the formation and evolution of single and multiple stars and clusters of stars in different parts of our galaxy.

The main goals

The main goals of the dissertation are:

1. To develop a method of direct determination of the complete set of the fundamental parameters of the components of a binary system on the basis of the combination of

speckle-interferometric and spectrophotometric observations with the radial velocities and parallaxes measurements.

2. To make a catalogue of spectral energy distributions of the main-sequence F,G and K speckle-interferometric binaries, to estimate their colors and to reinvestigate their entire spectral types.

3. To observe several chosen objects by means of speckle-interferometric techniques in order to reconstruct their visual orbits, measure their Δm and obtain their absolute magnitudes.

4. To build individual spectral energy distributions for the components the selected systems by means of atmospheres modeling combination with their measured magnitude differences and known parallaxes. Hence, to determine their complete set of fundamental parameters: effective temperatures, luminosities, spectral types, masses, gravity accelerations and ages.

5. To investigate advantages and restrictions of the developed method in the revision of the existing statistical dependencies.

New scientific results

To developed method of direct determination of the fundamental stellar parameters was investigated on the basis of the combination of speckle-interferometric and spectrophotometric observations of binary systems.

Composite spectral energy distributions of 46 speckle binary stars were measured for the first time. The measurements were made at the Cassegrain focus of the Carl Zeiss Jena (Zeiss–1000) 1 m telescope of SAO. The measured SED's covered the range between 3700Å and 8300Å. The BVR magnitudes A good agreement has been found between the calculated colour magnitudes and colour indices and those of Hipparcos and Tycho catalogues. Also a comparison of the estimated spectral types with those given by SIMBAD (http://simbad.u-strasburg/Simbad) shows a good agreement for most of the stars within the error values of $B-V$. and the $B-V$ colour indices for all of the 46 stars were calculated, and their composite spectral types were estimated.

New relative positions of five speckle interferometric binary systems were measured using the speckle interferometric techniques at the 6-meter telescope of the Special Astrophysical Observatory (SAO RAS), these are: 41 Dra, COU 1289, COU 1291, HD 25811 HIP 689. For the first time, modified orbital elements of these stars were obtained. Their magnitude differences were estimated and they were combined with Hipparcos parallax (ESA 1997) and the known entire V magnitude to calculate the absolute magnitudes of their components, and hence their spectral types.

For the first time, individual theoretical SEDs were build for each of the two components of the binary systems: 40 Dra, 41 Dra, COU 1289, COU 1291, HD 25811 and HIP 689. The method used Kurucz (1993) line-blanketed plane-parallel model atmospheres combination with the results of speckle interferometry and spectrophotometry.

Presentations

The main results of this work were presented in the following international conferences and seminars:

The Second Arab Astronomical Conference (Amman, Jordan; 8 - 10 September 1997);

The First All-Russian Astronomical Conference (Saint Petersburg; 6 - 12 August 2001);

IAU Symposium No. 210, Modelling of Stellar Atmospheres (Uppsala, Sweden; 17-21 June 2002);

The 5th Arab Astronomical Conference & The 3rd Conference for AUASS (Amman, Jordan; 19 - 22 August 2002);

The sstrophysical seminars at the Special Astrophysical Observatory (SAO) (Nizhnij Arkhyz), and at the Higher Institute of Astronomy and Space Sciences, Al al-Bayt University, Mafraq, Jordan.

Main items proposed for defense

1. The results of spectrophotometric study of 46 speckle interferometric binary systems, which include their entire spectral energy distributions in the range 3700-8400 Å, BVR Johnson-Cousins magnitudes, $B - V$ magnitude differences, and their entire spectral types.

2. The results of speckle interferometric measurements of 41 Dra, COU 1289, COU 1291, HD 25811 and HIP 689, which include measurements of their relative positions, determination of their orbital parameters, mass sums and magnitude differences.

3. Results of the combination of speckle interferometry and spectrophotometry with the atmospheres modeling to estimate the fundamental parameters of the components of 40 Dra, 41 Dra, COU 1289, COU 1291, HD 25811 and HIP 689. The parameters include their spectral types, luminosities, effective temperatures, radii, masses, gravity accelerations and ages.

Personal input of the author

Speckle interferometric observations and data reduction were made together with the group of The Laboratory of High Resolution in Astronomy (SAO RAS). The final estimations and results were made by the author.

All spectrophotometric observations, data reductions, atmospheres modeling and results extraction were made by the author.

Contents of the dissertation

This dissertation consists of introduction, four chapters, conclusion, bibliography of 120 items, and appendix. It consists of 172 pages including 53 figures and 54 tables.

In the ***Introduction*** the importance of the work was explained in addition to the actuality, the main goals, the new scientific results, the presentations, the main items proposed for defense, the personal input of the author, a brief contents of the dissertation and a list of the author's publications.

In the 1st chapter ***The Astrophysical Problems of Studying Binary Stars*** brief review of modern knowledge in the field is given, including relationships between fundamental stellar parameters and the formation and evolution theories. Conclusions were made about the low precision of the statistical dependencies of mass-luminosity, mass-radius, age-luminosity and the scale of the effective temperatures with the comparisons of theoretical models. The concepts of improvement of these statistical dependencies were discussed on the basis of the complex study of visual close binary stars which depends on the combination between speckle interferometry, spectrophotometry, radial velocities and parallaxes. At the end of the chapter, the stars selection criteria to apply the direct method of estimation of the fundamental parameters were discussed.

In the 2nd chapter ***Speckle Interferometry of Binary Stars***, description of the speckle interferometric method of measuring relative positions and magnitude differences of binary and multiple systems is presented.

The method enabled us to achieve high accuracy measurements of the relative positions of binary stars using large ground based telescopes.

Although diffraction limit of the telescope $\alpha = 1.22\lambda/D$ is only several milli-arc-seconds ($0\rlap{.}''02$ in the case of BTA), resolution of ground telescopes is rarely more than $1''$.

The main reason which decreased the resolution is the turbulence of the earth atmosphere. However, at exposures comparable to the atmospheric turbulence time (which freeze the atmospheric degradation), monochromatic images of the stars powerfully save information with the diffraction limits of the telescope.

The statistical processing method proposed by Labeyrie A.(1970) enables obtaining power spectra or auto-correlation functions of the set of instant images of the source. In the case of binary stars, the method made it possible to determine relative positions and relative intensities of the components using geometrical parameters and fringes contrast of the measured power spectrum.

The system used to obtain speckle interferometric data at the prime focus of BAT was discussed along with the procedures of processing the sets of speckle interferograms, determination of the relative positions and magnitude differences of the binary and multiple stars.

The method was applied to five binary systems: 41 Dra, Cou 1289, Cou 1291, HD 25811 and HIP 689. The results of observations performed in 2001 and 2002 include their relative position measurements with accuracy $0\rlap{.}''001$– $0\rlap{.}''003$ and magnitude differences with accuracy $0\rlap{.}^m04$– $0\rlap{.}^m12$ (Al-Wardat et al. 2003). Improved orbits for the five systems were archived using the new points along with those from the Fourth Catalog of Interferometric Measurements of Binary Stars, the new estimated orbital elements were compared with the other authors. Direct proof of 15 years period for the system COU 1289 was obtained, the system was resolved three times during the closest approach of its components when the angular separation was between $0''.018$ and $0''.019$.

The computed orbital parameters and magnitude differences were combined with the parallaxes, from Hipparcos, to derive the mass sums, the individual absolute magnitudes and the spectral types of the components. The accuracy of the estimated masses and absolute magnitudes depends, mainly, on the errors of the used parallax.

In the 3rd chapter ***Spectrophotometry of Binary Stars***, a wide range ($\sim$4500 Å), low resolution (18 Å, 6 Å/px) spectrophotometry of 46 speckle interferometric binary stars were presented, where I got their entire spectral energy distributions, BVR magnitudes, $B-V$ colour indices, and their entire spectral types. The objects of the study were taken from the speckle interferometric programme, which has been carried out at the 6-m BTA telescope of the Special Astrophysical Observatory since the early nineties. The programme mainly includes late type dwarfs in the vicinity of the Sun, which fundamental parameters are badly known.

Beside the direct results of these observations, a part of the presented data were used as a reference for building theoretical spectral energy distribution curves on the basis of Kurucz blanketed models. These along with the magnitude differences from speckle interferometric observations, were used to build spectral energy distributions for the components of the binary systems, from which we got their complete set of fundamental parameters (see chapter 4).

The stars were divided into three sets (Set A, Set B and Set C) according to the observational campaigns. The spectra were obtained using a low resolution grating (325/4° grooves/mm, 5.97 Å/px reciprocal dispersion) within the UAGS spectrograph at the Cassegrain focus of the Carl Zeiss Jena (Zeiss–1000) 1 m telescope of SAO during the photometrical nights: January 28 and February 4, 2002 for set A; May 25, 26 and 27, 2002 for set B; and July 20 and 21, 2002 for set C. The seeing in all nights was around $1.5''$. The stars are listed in three tables, which include their different identifications, coordinates and times of observations in Julian Date.

The used spectrograph has an ISD015 A 530×580 px CCD detector, its parameters and sensitivity curves at the blue and red parts of the spectrum are shown in the chapter.

A well known standards were used for the calibration and investigation of the external agreement of the system. The standard deviation of B and V magnitudes, obtained for each star from the sample of the spectra, was typically better than $0\overset{m}{.}06$, and for the R band it was better than $0\overset{m}{.}07$.

The results of the measured flux, corrected for the atmospheric extinction, are listed in the Appendix and plotted in the chapter in units of $erg/cm^2 \cdot s{\cdot}\text{Å}$.

BVR synthetic magnitudes were computed using the zero points of the spectrophotometric calibration of Vega. For V band ZP was solved using the spectrophotometric calibration of Vega published by Hayes (1985) and the V magnitude of $0\overset{m}{.}03$ measured by Johnson et al. (1966). While for B and R bands it was solved using the Vega magnitudes published by Hamuy et al. (2001) as $B = 0\overset{m}{.}014$, and $R = 0\overset{m}{.}042$.

A good agreement has been found between the calculated colour magnitudes and colour indices and those of Hipparcos and Tycho catalogues.

The entire spectral types of the binaries were estimated by comparing $B - V$ with the intrinsic colours of FitzGerald (1970). The comparison of the estimated spectral types with those given by SIMBAD showed a good agreement for most of the stars within the error values of $B - V$.

In the 4th chapter ***Physical Parameters of the Components of Binary Stars***, I presented the study of six binary systems (the quadruple system ADS 11061, the binary systems COU 1289, COU 1291, HD 25811 and HIP 689) as examples for the combination method of atmospheric modeling with the observational results of speckle interferometry and spectrophotometry to estimate the fundamental parameters of their components.

The description of each system started by introduction about the system includes its importance in such study, list of data concerning the system from different sources like SIMBAD, Hipparcos and other sources. Followed by individual description of spectrophotometrical results.

Using the magnitude differences from the results of speckle interferometry and the entire visual magnitudes from the spectrophotometric results, the individual magnitudes of the components were calculated. These along the parallax were used co calculate the absolute visual magnitudes, from which we estimate the preliminary effective temperatures, radii and gravity accelerations. This allows construction of model atmospheres for each component using the grid of the Kurucz (1994) blanketed models.

The entire SED's of these pairs from the spectrophotometric results were used as a reference for the best fitting with the theoretical ones, and for the feedback of the parameters of their components. Hence the complete set of parameters of each component were estimated including: effective temperature, luminosity, spectral type, mass and gravity acceleration.

The positions of systems components on the evolutionary tracks and isochrones of Girardi et al. (2000) were assigned, and their ages were estimated. Formation and evolution of the systems were discussed according to the formation theories, where filament fragmentation was proposed as the most likely process for the formation and evolution of the quadruple system ADS 11061, and Fragmentation was proposed as the most likely process for the formation and evolution of the systems COU 1289, COU 1291, HD 25811 and HIP 689.

In the ***Conclusion***, the main results of this work were listed.

Particulary, we developed a complex method of estimation of the fundamental stellar parameters of the components of binary and multiple systems of stars. The method depends on the combination between speckle interferometry, spectrophotometry and atmospheres modeling.

The method uses the magnitude differences between the components and the mass sums of the systems measured by means of speckle interferometry with the entire spectral energy distributions and apparent magnitudes of the systems measured by spectrophotometry to build individual theoretical SED for each of the subcomponents using Kurucz (1993) line-blanketed plane-parallel model atmospheres. From which we estimate the complete set of the fundamental parameters of each component of a binary system.

The method was applied to a sample of six speckle interferometric binary systems of the nearby F-type dwarfs, these were: 40 Dra, 41 Dra, COU 1289, COU 1291, HD 25811 and HIP 689.

The orbital elements of the studied systems, their magnitude differences, absolute magnitudes, mass sums and spectral Types were estimated in addition to the the complete set of the individual fundamental parameters of the components (effective temperatures, luminosities, spectral types, masses, gravity accelerations and ages).

The estimated parameters forms the most detailed and accurate ones ever estimated for the studied systems. Comparisons with the known relations for disk late-type dwarfs has been made.

In addition we got the entire SEDs for 46 speckle-interferometric main sequences binaries. These data give an opportunity to improve statistical dependencies for the nearby stellar populations. The results can be used for the study of formation and evolution of binary and multiple systems.

The ***Appendix*** includes the tables of the spectral energy distributions for the 46 stars studied in chapter 3.

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11. Al-Wardat M. A., Balega Yu.Yu., Pluznik E.A., Shkhagosheva Z.U. Speckle interferometric results and modified orbits of five binary systems, Spec. Astrophys. Observatory, Preprint # 190

Chapter 1

The Astrophysical Problems of Studying Binary Stars

The term binary star refers to a system containing two stars held together by their mutual gravitational attraction, revolve in close elliptical (or circular) orbits around their common center of gravity and have a common proper motion through space.The importance of studying binary stars lies in more than one area. Firstly, it is the only direct method for the evaluation of stellar mass, one of the most important parameters of the stars. Secondly, it plays an important role in studying the formation, evolution and mass loss of stars. Thirdly, the spatial arrangement of the orbital planes of wide visual binaries in clusters or in small regions in the galaxy may play a role in interacting galactic dynamics (Lippincott, 1992). In this chapter we will briefly go through the history of binary stars, their statistics, classification, formation theories, and their evolution.

1.1 Milestones in the history of binary stars

1767 : Reverend John Michell in a paper read before the Royal Society of London, realized that many double stars which appear to consist of two stars placed close together in the sky must in fact be in close physical proximity to each other, arguing that the frequency of near stars per unit area around a given star often exceeds that expected for the observed average surface density. Michell thus has the credit of being the first to establish the existence of physical systems among the visual double stars.

1802 : Sir William Herschel coined the term "binary star" and defined it to designate "a real double star - the union of two stars that are found together in one system". And he discovered the first binary systems.

1824 : W. Struve detected around 3000 binaries among 120,000 stars surveyed them using Fraunhofer refractor, which for the first time was equipped with an excellent driving clock and thus allowed to make precision measurements.

1827 : F. Savary and by J.F. Encke solved the problem of deriving the orbital elements of a visual binary star, utilizing four complete measures of angle and separation.while Sir John Herschel in 1832 added another method based solely on angle measurements.

1842 : Ch. Doppler discovered the Doppler effect, which without it we would not know the masses of stars, the masses of galaxies, nor the Hubble constant.

1847 : Sir John Herschel (the son of Sir William Herschel) issued the Results of astronomical observations made during 1834- 1838 at the Cape of Good Hope, i.e. the first catalogue of binary stars in the southern hemisphere (417 entries, for the first time ordered in Right Ascension).

1850 : Otto Struve (the son of W. Struve) published what became known as the O Σ or Pulkovo close double star catalogue (408 entries).

1861 : F.W.Bessel, A. Auwers, A.G. Clark found and analyzed the variable proper motion of Sirius, and ultimately discovered its faint, white dwarf companion.

1905 : S.W. Burnham published his General Catalogue of (13,665) Double Stars within 121 Degrees of the North Pole. Also Campell and Curtis published the First Catalogue of Spectroscopic Binaries, with 140 entries, based on measurements with the Mills Spectrograph at Lick Observatory.

1932 : R.G. Aitken published the New General Catalogue of (17,181) Double Stars.

By this, we find ourselves in the present epoch with the first serious census of the binary frequency of Heintz (1969), see section 1.4.

1.2 Classification of binary stars

It is natural to classify such large number of stars into sub-classes to simplify their study. Many efforts were made in this field, over here we will display some of these schemes.

One of the schemes classify binary stars according to the observational means into the following categories (Batten,1992; Plavec, 1992):

Visual binaries; the binaries which instantly seen to be double stars through the telescope. Although some of these pairs are chance alignment of stars at very different distances from us, many are genuine binary systems. Recognition of a visual binary depends not only on the true separation of its components, but also on its distance from the sun. So, at least those systems for which orbits may be determined, are relatively near neighbors.

Spectroscopic binaries; the binaries which cannot be seen as double even through a large telescope, but one can recognize two spectra or periodic motion of one spectrum. They can be recognized at much greater distances than the visual binaries.

Eclipsing binaries; the binaries which can be recognized by the variation of their light caused by mutual eclipses of two components. They can be recognized at even greater distances than the spectroscopic binaries if the eclipses are fairly deep.

Astronomical binaries; the binaries in which the companion cannot be seen directly, but from the periodic motion of the brighter star its presence can be inferred.

Interferometric binaries; the binaries which are best measured by studying the interference patterns produced by the two stars.

There is an objection on this scheme of classification, however, is that it does not correspond to any obvious physical differences between the classes, i.e. a binary star may classified under more than one category. Another scheme classify binary stars according to the separation between the pair into the following categories (Batten 1992; Plavic 1992):

Wide binaries; the binaries in which the separation of the two components is enough so that they don't affect each other evolution, like most of the visual binaries.

Close binaries; the binaries in which the two components interact in many ways and affect each other evolution, under this category we may insert many of the spectroscopic, eclipsing, and unusual types of objects resulting from interaction between the components of the close binary , like cataclysmic variables and X-ray binaries. Binaries under this category can be classified into three sub-groups according to the Roche Model (Kopal 1959) :

- Detached systems; in which neither component fills its Roche lobe.
- Semidetached systems; in which the secondary fills its Roche lobe, while the primary (more massive) star is smaller than the Roche limit.
- Contact systems; in which both components appear to fill their Roche limit.

1.3 Binary star formation mechanisms

The capture theory: Proposed by G.J. Stoney (1867), as a two stars, originally independent, might approach each other under such conditions that each would be forced to revolve with the other about a common center of gravity. This theory in its original form has been completely abandoned as too unlikely (Zinnecker 2001).

The tidal capture theory:A modern version of the capture theory, applicable to dense star clusters such as globular clusters (Fabian Pringle & Rees 1975) or the theory of gas drag in colliding protostars with extended disks or envelopes (Silk 1978). In fact, these processes may be at work in the core of young clusters to explain the high frequency of tight binaries among massive stars (Mermilliod & Garcia 2001).

The separate nuclei theory: Advanced by Laplace in 1796.

The fission mechanism: First discussed by Lord Kelvin and P.G.Tait in 1883. This theory describes the behaviour of a rotating,homogeneous, incompressible fluid mass, as a sequence of equilibria under gravitational contraction.

In 1918, Jeans made a famous conjecture that fission is the formation process of close binaries, depending on Jacobi discovery in 1834 for the sequence of non-axisymmetric