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ASTROMETRY OF DOUBLE STARS

Introductory Lecture

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1. Introduction

Progress in the study of visual binaries depends upon the existence of a series of astrometric observations in addition to observations of their relative motions. The present paper discusses the proper motions, parallaxes and mass-ratios of visual binaries, the detection of astrometric binaries and the photographic astrometry of faint binaries.

2. Proper Motions

The earliest proper motion studies were based, of course, entirely upon meridian circle observations. In fact, it was such observations that led to the discovery of the duplicities of both Sirius and Procyon.

Any discussion of proper motions in a fundamental system, such as the FK4, ultimately depends upon meridian circle observations. Although there has been no deliberate attempt to exclude double stars from meridian circle or photographic star catalogue programs, there are a substantial number of binary systems which are difficult to observe and for which there are still insufficient data in regard to their proper motions.

Below 0.″5 separation, a binary appears as a single star in the field of a meridian circle, and therefore presents no problem for observing. For the pairs wider than 2″ which appear separated, normally only the brighter component is observed. However, if the pair is of special interest, both components are observed. Between 0.″5 and 2.″0 separation, binaries appear elongated and are therefore difficult to observe. Objects in this category are usually left for the astrographic cameras where they appear single.

Because of the necessary limitation in the number of stars included in any meridian circle program, relatively few binaries have an extensive meridian circle history and, in general, their proper motions are obtained from the photographic star catalogues.

The new international program of the AGK3, which is near completion, will contain proper motions with a high degree of homogeneity to a limiting visual magnitude of 10. The catalogue will be on the FK4 system and will contain some 200000 stars north of $-2°$ declination. The expected mean errors of these motions will be approximately 0.″8 per century in both coordinates.

A second program is directed at similar improvements of the proper motions in the Southern Hemisphere. The meridian circle observations for approximately 20000 reference stars are already in progress with eleven observatories participating. Two independent photographic programs based upon this reference star catalogue will

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produce proper motions of some 200000 stars. One program is in progress at the Cape Observatory; the other is in the planning stage at the U.S. Naval Observatory, where the observations will be carried out in Argentina.

As early as the Moscow meeting in 1958, Commission 8 of the IAU directed that special attention be given to double and multiple star systems which are difficult to measure on photographic plates taken with cameras of relatively short focal lengths. Later on, at the 1964 Hamburg meeting of the IAU, the Special Committee of the same Commission established criteria for selection of such stars and a selection has since been made by T. E. Corbin [1] of the U.S. Naval Observatory.

This list contains 2292 stars selected from a magnetic tape copy of the Index Catalogue of Visual Double Stars. The selection was based upon the brighter component having a magnitude between $6^m.0$ and $9^m.0$, the magnitude difference between components being $4^m.0$ or less, and the separation of the components falling within the limits $2''.0 < S < d$, where $d = 29.0 - (m_B + m_F)$, S is the separation of the components, and m_B and m_F are the magnitudes of the brighter and fainter components. Northern stars from this list, in the zones from $+70°$ to $+30°$ and from 20° to 0°, are under observation at Strasbourg and Bucharest, respectively. Southern stars on the list are understood to be included in the meridian circle program now being conducted by the Pulkovo and Chilean astronomers at Santiago, Chile.

The program of the U.S. Naval Observatory seven-inch transit circle includes 1272 close binaries selected by G. van Herk [2] with separations less than $1''.1$. Observations of some of these stars were completed while the instrument was located in Washington. The remaining observations will be made during the Southern Reference Star Program now in progress with this instrument at El Leoncito, Argentina.

These efforts in meridian astronomy are highly important in providing uniform data on proper motions of the brighter binary systems, and are essential to a knowledge of their space motions and to the distinction between physical and optical pairs. I am sure any support and interest that the double star astronomers can express for this type of work will be appreciated by the meridian astronomers.

There are, of course, a number of other catalogues with proper motion data such as the Yale and Cape zone catalogues, and the zones of the Astrographic Catalogue (CdC), which have been repeated, as well as the two McCormick Catalogues. While both the Astrographic and McCormick Catalogues have fainter limiting magnitudes than the other catalogues previously mentioned, they are not on the same fundamental system.

Among other major contributors to photographic proper motion catalogues are the Radcliffe, Pulkovo and Groningen Observatories. Special mention should also be made of the value of the Bruce and Palomar Schmidt surveys carried out by W. Luyten [3] and the Lowell Survey carried out by H. Giclas [4] and his associates.

It should perhaps be emphasized here that any collection of old plates with well defined stellar images, taken with instruments of moderate to long focal length, could be used for the purpose of deriving proper motions of special objects or areas, if new plates were to be taken with the same centers as the old.

3. Trigonometric Parallaxes

The first three successful attempts to measure trigonometric stellar parallaxes included the two well-known binary systems 61 Cygni and α Centauri.

That the early visual methods of measuring stellar parallaxes were slow and not very precise is seen from the fact that, at the beginning of this century, there were only 72 stellar parallaxes determined, 15 of which were grossly in error. Thirty-one of these stars were double or proper motion pairs. However, all this work is now only of historical interest.

The modern period started in 1903 with Schlesinger [5] using the 40-inch Yerkes refractor. Not only did Schlesinger devise the photographic method for determining stellar parallaxes, but he also succeeded in organizing an international cooperative effort of large scale parallax determination in which about a dozen or so observatories possessing long-focus refractors participated.

As a result of this international undertaking, Yale University Observatory was able to publish, by 1950, a *General Catalogue of Trigonometric Stellar Parallaxes* of 5822 stars, based upon some 10000 determinations. The supplement to this catalogue, published in 1963, added parallaxes for an additional 577 stars.

The scheme drawn up by Schlesinger called for the observation of all stars as bright as magnitude 5.5, except for stars of spectral type earlier than A, and late type giants for which only very small parallaxes are expected. Observations of all of these stars have been completed from pole to pole. In addition, many more stars for which large parallaxes were expected have also been observed. These latter stars, selected mostly because of large proper motions, include many of the intrinsically faint stars nearer than 25 parsecs. A majority of these appear in the Supplement to the Yale Catalogue.

The average accidental probable error of a parallax in the Catalogue is $\pm 0\overset{''}{.}011$, which is entirely too large to determine the mass of a binary star with an acceptable degree of precision of 30% or better, except for approximately 20 binary systems with well-determined orbital elements having parallaxes in excess of $0\overset{''}{.}1$.

Based upon substantially more material than that generally used in determining the average parallax in the Catalogue, and, preferably, by use of independent determinations with two or more telescopes, trigonometric parallaxes can be determined with a probable error of $\pm 0\overset{''}{.}005$. It seems unlikely that a smaller probable error can be achieved by present methods. This then means that, for binary systems with parallaxes less than $0\overset{''}{.}050$, the masses of the systems will have probable errors in excess of 30%.

At the present time approximately 20 systems have well-determined orbital elements, and parallaxes in excess of $0\overset{''}{.}1$, as has already been mentioned. A similar number have parallaxes between $0\overset{''}{.}05$ and $0\overset{''}{.}1$. Another 25 systems with well-determined orbital elements could give valuable data on stellar masses if parallaxes and mass ratios were obtained.

Binaries for which a minimum parallax of $0\overset{''}{.}050$ is not required to obtain accurate masses are those belonging to the Hyades cluster, which has a mean parallax of 0.″024 with a mean error of the order of 2–3%.

However, even if the mass ratios were known for all of these systems, the total number of stars would be entirely too small to provide a representative sample of stellar masses – except, perhaps, in the middle range of the main sequence.

The use of photometric parallaxes obtained by fitting the mean component to the Pleiades-Hyades main sequence, as first done by Eggen [6] provides an important additional method of determining stellar masses.

4. Mass Ratios

Except for a few special cases, the early mass-ratio determinations were based upon meridian circle observations. For example, the Boss General Catalogue of 33342 Stars lists the mass-ratios for 25 binaries. In 1916 G. Van Biesbroeck [7] recognizing the need and importance of mass-ratio determinations, added a number of binaries to the regular parallax program at the Yerkes Observatory. These objects were to remain on the program after measurement of their parallaxes for the purpose of eventually producing sufficient material to determine their mass-ratios.

Approximately 50 binary systems are on the Yerkes list, and the observing material is potentially one of the most valuable sources we have at the present time for mass-ratio determinations, assuming the series is continued. Preliminary results for 19 double stars on the program were published by R. C. Huffer [8] in 1934. His results have since been superseded by later investigations based upon considerably more material primarily carried out by R. G. Hall [9].

At the present time, active programs on mass-ratio determinations are being continued at the McCormick and Sproul Observatories. Both programs were initiated by P. van de Kamp. The McCormick program began in 1935 with ζ Herculis, which had early plates dating back to the parallax series of 1919. The Sproul program, with some 60 binary systems, came into being in 1938 with 85 Pegasi, for which the early plates date back to 1912. Both programs are being continued in realization of the fact that while, theoretically, a short arc with a measurable curvature is sufficient to establish the ratio between the dimensions of the relative and absolute orbits for a given system, observations over a long time interval are generally required to attain the necessary precision.

In a substantial number of cases, a problem exists in determining the final value of the mass-ratio. These are the cases where the visual binary is not resolved photographically, but appears as a blended image on the photographic plate. If the measured position of the blended image is identical to the weighted center of light intensity of the components, then the position of the barycenter can be determined – provided the magnitude difference between the components is known. However, experiments with close artificial binaries by R. G. Hall [10], and blended images by means of objective gratings by B. H. Feierman [11], have shown that the measured center of the blended image does not always coincide with the weighted center of light intensity, and especial-

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ly not for magnitude differences larger than 1.5 mag. There also appears to be a dependence upon the separation of the blended components. These differences have a direct bearing on the adopted mass-ratios.

Both in regard to parallaxes and mass-ratios of visual binaries, we are faced with the very serious problem of lack of participating observatories. Since Yale discontinued its program in the southern hemisphere, there is no active program in that hemisphere and aside from the Allegheny, Sproul, and McCormick programs in the northern hemisphere, there seems to be a general tendency to concentrate on the parallaxes of faint stars.

5. Astrometric Binaries

Aside from Sirius and Procyon, both bona fide visual binaries after the discoveries of their fainter companions, the classical cases of astrometric binaries are the components in ζ Cancri and in ξ Ursae Majoris, found in 1888 and 1907 by Seeliger [12] and Nørlund [13] respectively.

Nørlund's discovery of a perturbation in ξ Ursae Majoris with an amplitude of 0.″05 and a period of 1.8 yr is the smallest amplitude derived from micrometer measures of a double star. It was also the shortest orbital period until Wolf 630 was discovered by G. P. Kuiper [14] in 1934 to be a binary with a period of 1.7 yr. Wright, in 1908, confirmed Nørlund's period from radial velocity observations secured at the Lick Observatory.

Photographic observations by the Hertzsprung method have led to the discovery that the components of a number of double stars are themselves astrometric binaries – notably, ζ Aquarii and 61 Cygni. The case of 61 Cygni has also been studied by Deutsch [15] at Pulkovo. The large amount of photographic material which has been accumulated over the past decade for this system leaves the previously published period of 4.8 yr in doubt and a new study is now in progress.

Binaries with suspected astrometric components include among others – 70 Ophiuchi and η Cassiopeiae. In both of these cases, extensive photographic material does not support the existence of perturbations, although van de Kamp reports indications of a perturbation with a period of 18 yr from his extensive parallax series for η Cassiopeiae.

Among the many thousands of parallax determinations of 'single' stars, only very few cases have been found where the observed positions could not be represented by uniform proper motions and parallactic orbits.

Even if a substantial number of these stars were binaries, they would, in general, escape discovery because of the very nature of conventional parallax determination which is based upon a small number of plates taken over a couple of years. The short period perturbations, owing to their small amplitude, would not be detected, and the long period perturbations with larger amplitudes, in general, would escape discovery during the short period of observation. This selection is substantiated by the studies carried out in the search of astrometric binaries by van de Kamp and his associates.

The first astrometric binary discovered from a parallax series was β Coronae Borealis. Based upon plates taken at the Allegheny Observatory between 1918 and 1927, Burns [16] suspected the star to show a perturbation with a period of the order of 10 years. He wrote Lick Observatory in 1931 requesting a check on the published 40.9 days spectroscopic period. The Lick observations from 1931–1942 were published by F. J. Neubauer [17] and confirmed a period of 10.5 yr, with a shorter period of 320 days. The 40.9 days' period was never confirmed.

Another early discovery of an astrometric binary from a parallax series is Ross 614, discovered by D. Reuyl [18] in 1936. A subsequent extended series of plates at the Sproul Observatory led to an accurate orbit, including the prediction of the most favorable time for visual detection of the companion. The companion was detected and photographed by W. Baade [19] with the 200-in telescope in 1955. Later on, it was found that Ross 614 had been observed visually as a binary by van den Bos [20] in 1939.

Several other astrometric binaries, such as α Ophiuchi, μ Cassiopeiae, ι Cassiopeiae, and Ross 52, were found in the Allegheny Observatory parallax program.

An actual systematic search for variable proper motions of nearby stars was started by van de Kamp [21] in 1937 at the Sproul Observatory. He included all single stars within 10 parsec, and a few beyond, which were within reach of the 24-in refractor. Nearly all stars were brighter than the 12th magnitude and, with few exceptions, north of the equator.

This program has produced some exciting results, such as Barnard's Star with its two planetary companions having masses of the order of Jupiter's, and Lalande 21185 with a companion ten times more massive. According to the latest count by van de Kamp, the number of unresolved astrometric binaries has been raised to a dozen, with several more apparently single stars suspected of being double. Van de Kamp's study has shown how essential long range continuous observing programs are for this type of work. I am sure that a similar program in the Southern Hemisphere would produce results just as exciting.

6. Astrometric Studies of Faint Double Stars

We shall next discuss the current astrometric work on faint binaries and faint companions of single stars.

As early as 1911 Hertzsprung, studying Groombridge 34, expressed a wish that large telescopes be used in looking for faint companions to known parallax stars – preferably with red sensitive plates. Such a systematic search was later carried out by Van Biesbroeck with the 82-in reflector at the McDonald Observatory. A number of intrinsically very faint stars were discovered, including Van Biesbroeck's star with an absolute visual magnitude of $19^{m}_{.}3$. This, according to Luyten, is the star with the second lowest luminosity – the faintest being LP464-53, which has a photographic magnitude of 22, and an annual proper motion of $1''_{.}06$. Needless to say, no attempt has been made to date to obtain a trigonometric parallax of this star.

The current U.S. Naval Observatory parallax program covering stars between 12.5

and 18 magnitude also includes long exposure plates for the purpose of searching for companions as faint as the 19th magnitude.

At the Uccle Double Star Conference, Luyten reported on his proper motion survey based on the Palomar Schmidt plates. From the completed area north of declination $+75°$, he estimated that there would be 10000 wide pairs with common proper motion, and with fainter components brighter than 21.5 photographic magnitude nearer than 100 parsec. This number equals and, perhaps, exceeds the total number of all types of binaries – visual, spectroscopic and eclipsing – now known to be nearer than 100 parsec. With a median photographic magnitude of 16.5, he estimated that the average absolute magnitude would be about $+11$, or slightly fainter. Luyten also pointed out that his results involved a considerable selection effect, especially in regard to separation, which, if taken into account, would substantially increase the total number of binaries. "Even with a very small symmetrical Schmidt image the smallest separation that can be observed is 1.″5 and then the components must be fainter than 16.5 pg magnitude and nearly of the same magnitude", according to Luyten.

The Lowell proper motion survey was based upon photographs taken with a 13-in triplet lens telescope of roughly half the focal length of the Palomar Schmidt telescope. With a limiting photographic magnitude between 16 and 17, and annual proper motions larger than 0.″27, roughly 3% of the stars with no prior proper motion history have been found to be doubles, and new companions to known proper motion stars have been found in nearly 1% of the cases.

The smallest separation which is discernible from the Lowell plates is about 5″ for pairs of nearly equal magnitude between 12–14 photographic magnitude. It is primarily from the Lowell program that the stars in the U.S. Naval Observatory parallax program have been selected; and visual and photographic observations of the 300 stars included in this program have so far revealed new doubles in 10% of the cases.

The binaries found in these surveys differ from the classical binaries in that most of them have red dwarf components occupying the lower part of the main sequence. A few percent have components which are white dwarfs or degenerate stars. Such binaries are, therefore, more representative of the stellar population in the solar neighborhood than are the classical binaries.

7. Conclusions

All of the programs I have described are considered to be of a classical nature – they are long ranged and therefore often termed 'pedestrian'. They are, however, essential to the progress of astronomy and must be continued. Without continued meridian circle programs in both hemispheres, neither the present nor any future fundamental system can be established and maintained, assuming no new type of instrumentation is developed which can accomplish the same results with less effort and expense.

Without the Luyten and the Lowell proper motion programs, how could the abundance of low luminosity stars, white dwarfs, subdwarfs, and late main sequence stars have been discovered?

Without the Sproul Observatory programs devoted to nearby stars, how could we have acquired observational proof of the existence of celestial bodies of planetary size outside our own solar system?

Hopefully, present programs in all of the fields I have discussed will be continued and the existing voids, especially in the southern hemisphere, will be filled.

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Discussion

Luyten: In about ten years' time it will be possible to obtain proper motions for *any* star brighter than photographic magnitude 21, and north of $\delta = -33°$, from the 48″ Schmidt plates. There is virtually no magnitude error, and ten years from now we should also know the corrections from relative to absolute.

Lacroute: Au sujet de la précision des mesures d'étoiles doubles au circle méridien je dois dire que l'on a souvent une impression de difficulté lorsque les étoiles sont serrées et je compte examiner à la fin de notre programme si la précision est diminuée. Je signale que je pourrai très prochainement communiquer des résultats améliorés par rapport aux résultats préliminaires de Dr. Dieckvoss grâce à la méthode de recouvrement que j'ai appliqué à ces données.

Heintz: Meridian observations of double stars have also been made at Munich; the catalogue was published in 1962. Those objects where the duplicity may cause difficulties and errors in setting are only a small fraction of the double stars.