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Stellar Multiplicity Discovery by Lunar Occultations

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ABSTRACT: The primary result of lunar occultation studies of multiple star systems is the discovery of new systems. Its use as a method of multiplicity discovery has been productive, although incidental to timing observations made by amateurs and professionals for 360 years. The capabilities and limitations as a method of discovering new double stars is discussed.

1. INTRODUCTION

Angular resolution is an essential observational task in completely characterizing stellar multiplicity. Under ideal conditions, the angular resolution capability of a single telescope is limited by the telescope aperture diffraction pattern. For a 1-m aperture, this is about $0''.12$ at visual wavelengths and scales inversely as the diameter of the entrance aperture. Atmospheric effects make necessary sophisticated observational techniques such as speckle interferometry in order to approach the theoretical resolution of the aperture. Stellar lunar occultations enable higher angular resolution than the telescope aperture allows, making it a useful complementary technique in double star research.

Lunar occultation is the oldest super–resolution telescope technique. The source of light inteference carrying angular resolution information in a lunar occultation obviously occurs before the aperture of the telescope and above the earth's atmosphere. The telescope's function is only to collect light and resolve the intensity variations as the earth and lunar motions combine to sweep by the diffraction pattern.

It is an inexpensive, simple, and powerful method for identifying multiplicity; however, the observer must be content with what the lunar motion allows to be observed. The development of the technique applied to stellar multiplicity discovery is reviewed. Capabilities and limitations are discussed for visual and photoelectric observations.

2. DEVELOPMENT OF THE TECHNIQUE FOR DUPLICITY DISCOVERY

A telescope is necessary to observe any useful detail of an occultation of a star by the moon. The precise moment and manner of disappearance are too subtle to be noticed by simply gazing at a bright star occultation. A clear stepwise extinguishing of starlight is a strong indication of duplicity, although this was not understood for more than 200 years after the first reported telescopic occultation observation was made by Gälileo in 1610.

Galileo recorded this occultation in a sketch showing the star's position relative to markings on the moon's surface. Ismael Boulliau, later known as Clarissimus Bullialdus after becoming a Roman Catholic priest and astronomer at the Paris Academy of Science, recorded the time of the occultation of Spica in 1632. He measured the altitude of the star as it approached ingress with an accuracy sufficient to be still useful in refining the lunar orbit 150 years later.

Bullialdus received one of Huygen's earliest pendulum clocks for his work. He also corresponded frequently with other astronomers and encouraged Johannes Hevelius to record occultation timings. It is not clear why the observations were made, nor does there appear to be any mention of peculiar occultations, despite Hevelius' reputation for having the best instruments and making careful observations.

Instrument making improved dramatically during the last half of the 17th century and during the 18th century, as did the accuracy of observations. In 1754, Johann Tobias Mayer, a mathematician and gifted observer, described his use of occultation timings to improve the observed positions of the moon. His incentive was both financial (an award was offered for a method to accurately determine the longitude of ships at sea) and theoretical (to more accurately test Newton's prediction for lunar motion). He was successful in both; however, even with this keen interest in occultations, there still appears to be no mention of peculiar stepwise occultations attributed to stellar multiplicity.

The concept of gravitationally linked double stars was well established by the beginning of the 19th century with the publication of William Herschel's double star catalogs. In 1819, a stepwise occultation was suggested to be the signature of a close double star by a Professor Berg of Vienna, who observed a reappearance of Antares. The fainter blue star appeared first and then was lost in the brightness of Antares. His suggestion of duplicity was soundly denounced in favor of lunar atmospheric refraction.

Nevertheless, the concept of super angular resolution was finally established and is described in John Herschel's book *Outlines of Astronomy* (1833). He suggests that "a double star, too close to be seen divided with any telescope, may yet be detected to be double by the mode of its disappearance." Antares' companion was observed numerous times at occultation during the 1840's and 1850's. Several different stepwise occultations were reported in the 1851 inaugural issue of *The American Astronomical Journal.* For over 150 years, single stars have joined the list of suspected or confirmed double stars by visual, telescopic observations of occultations and photoelectrically for 40 years.

3. CHARACTERISTICS OF DOUBLE STAR OCCULTATIONS

The meaningful characterisitcs of a double–star occultation are simplest for visual, telescopic observations. They are the stepwise change in brightness signifying possible duplicity, the elapsed time between the brightness changes, and the predicted angular velocity of the lunar limb at the position angle of the occultation. The product of the elapsed time and angular velocity gives a projected separation that is less than the true angular separation, unless by luck the position angle of the lunar limb and double system are in phase.

Experienced visual observers can estimate changes of 1/4 or so in intensity (approximately 1.5 magnitudes) and time intervals of 1/4 second under favorable conditions. The moon's vector angular motion relative to the stars ranges from near zero at grazing to about $0''.6\ \mathrm{sec}^{-1}$. Most occultations occur within the limb angular velocity range of $0''.2$ to $0''.5$ sec^{-1} or angular resolutions of $0''.05$ to $0''.13$. The former is the aperture diffraction limit of a 2.4-m telescope. The advantage of visual observations as a discovery technique is its low cost, and amateurs all over the world can contribute with small telescopes at less than ideal sites. However, visual observations of a nonrepeatable event lasting a few seconds to a fraction of a second can at best provide only a warning of duplicity. Several confirming independent observations do provide some assurance of duplicity.

Higher angular resolution and improvement in objectivity are obtained with high-speed photoelectric photometry. Sequential integrations of 0.001 sec are sufficient to record the occultation diffraction patterns whose time duration is a function of the limb velocity, lunar distance, and wavelength. A typical time duration of a diffraction pattern is about 0.050 sec. The angular resolution of a photoelectric record of two completely separated patterns end to end is $0''.010$ to $0''.025$, assuming the previously mentioned limb velocity range. For projected angular separations less than about $0''.010$, the diffraction patterns overlap. However, resolutions of about $0''.005$ can be inferred from model fitting.

Knowing the lunar distance and optical bandpass, a diffraction model can be fitted to the data using differential correction, least-squares techniques. The fitted fringe spacing yields the actual angular velocity of occultation. The mean intensities and the time of pattern separation, even if they overlap, can be determined with surprising precision because the general shape of the pattern is known, the pattern is defined by some 50 integrations, and the observation is completed in less than a second. Rule of thumb errors and ranges are given Table I.

TABLE 1. **Approximate Errors of Occultation Double Star Measurements**

Measured Quantity	Technique: Visual	Technique: Photoelectric
Limb Angular Velocity	Predicted	$\pm 0''.001$ sec^{-1}
Timing	± 0.2 sec	± 0.002 sec
Magnitude Difference	± 0.2	± 0.04
Magnitude Range	~ 2 mag	~ 3.5 mag
Limiting Angular Resolution	$0''.05 \pm 0''.05$	$0''.005 \pm 0''.002$

Photoelectric records are sufficient for detailed interpretation of the diffraction pattern including local limb slope measurments and astrometry. A double system's true angular separation in the plane of the sky is projected onto the direction of motion of the occulting lunar limb. Several projected angular separations at different angles can be combined to determine the true separation; however, other repeatable techniques are better suited for astrometry.

As a method of random multiplicity discovery, occultations attain the highest angular resolution. By observing in the blue, red, and infrared, dramatic color contrasts can be used to advantage. Although the projected resolution is random such that some resolvable systems will have too small a projected separation to be resolved, occultations are immune to orbital plane inclination

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that may minimize radial velocities and other spectral characterisitcs that may make spectroscopic detection difficult.

The occultation method is thoroughly covered by Nather & Evans (1970), Evans (1970), and Nather & McCants (1970). A concise review with extensive references is contained in Brian Warner's *High Speed Astronomical Photometry* (1988).

4. PRODUCTIVITY OF MULTIPLICITY DISCOVERY

In 18.6 years, the moon sweeps out a 10°.2 strip of sky centered on the ecliptic. Although restricted, statistically all common spectral types and apparent brightnesses are included as well as the galactic plane, the Hyades, and the Pleiades. *The Zodiacal Catalog* contains 3,539 stars brighter than 7.5 magnitude that can be occulted by the moon. Less than half have been reported as having been observed at occultation. The many stars between 7.5 and 9.0 mag have barely been sampled, leaving many candidates and potential doubles yet to be observed.

Over 140 years of visual occultation timings for the purpose of improving the lunar ephemeris have also identified hundreds of new or suspected doubles. Appleby (1980) noted that, out of some 80,000 visual occultation observations of 3500 stars from 1943 to 1977, 423 stars were observed to have peculiar disappearances. Of those, 160 (38%) were found to be known doubles. This is a higher percentage than the approximately 20% expected from random observations (Shara *et al.* 1987), supporting the conclusion that peculiar disappearances indicate possible duplicity. Appleby calculates that possibly another 166 are new doubles.

Presently a compilation of occultation double stars is being maintained by a volunteer organization, the International Occultation Timing Association (IOTA), Dr. David Dunham, president.

Evans (1983) found that, in an eleven–year systematic program of photoelectric occultation observations of stars down to 9th magnitude, 7% were double or multiple stars. This does not include doubles previously found from other types of observations. For stars brighter than 6.7 magnitude, he found 17% to be resolved doubles.

A conclusive assessment of the reliability of double star detection was not possible with the data available to Evans. That data included mostly data recorded at the McDonald Observatory. A similar program was maintained at the Lowell Observatory, and those results are being prepared for publication. A preliminary comparison of the McDonald and Lowell data indicates a high degree of reliability.

Some 2,700 different stars were observed at McDonald, and 1,800 at Lowell; 462 stars were observed at both observatories on the same dates. At both locations, approximately 6% of the stars had traces that indicated duplicity. Eighty percent of the McDonald doubles were confirmed by Lowell observations. A portion of the remaining 20% that were not confirmed may be doubles but not confirmed because of noisier traces due to local conditions for that event. The suggestion therefore is that at least three–quarters of the stars whose photoelectric traces indicate duplicity are likely to be double. This assumes the same care in observations and reductions and astronomical quality of the sites exhibited by the McDonald and Lowell Observatories.

In conclusion, double star discovery through occultation observations is still a viable complementary technique in double star research. Modest equipment and small telescopes often available to colleges and amateurs around the world are sufficient. Even visual observations can provide some indication of suspected duplicity. By sheer numbers of observers, one could expect a significant number of real discoveries to be reported. These results would continuously provide excellent candidates for follow–up speckle observations. However, recognition of its usefulness, organization, and support are required for this serendipitous approach to be successful.

5. REFERENCES

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6. DISCUSSION

ABT: Where can we find a recent compilation of occultation measures since Evan's 1983 list?

WHITE: The International Occultation Timing Association directed by David Dunham maintains a data base.

SCHMIDTKE: Dunham's catalog must be used with care because it is a compilation of known and suspected binaries of all types: occultation, spectroscopic, eclipsing, etc. Thus, many entries have no history of occultation observing! Unfortunately, nearly all entries for bright stars are included in the *Bright Star Catalog*, including fictitious references to occultation separations as small as 0.01 mas.

WHITE: One must use the catalog not as a list of definite new doubles, but as a fertile list to be culled for true close doubles. It is updated regularly with newly observed occultation doubles.

LEWIS: You said nothing about your current system. Are you still using PMT's, or have you gone on to CCD's or other equipment enhancements?

WHITE: We do not do routine occultation observations any longer at Lowell. However, our three-channel high-speed photometer is used for unique events. We have also completed a very low resolution prism spectrograph (about 50 Åper pixel) for multi-color occultation observations using a CCD.

POPPER: Can you give some information on the statistics of spectral type and luminosity classes (to a limiting magnitude) of stars that are occulted by the moon?

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WHITE: Mostly G and K stars. A useful limiting magnitude is $V = +9$ for a 1-m telescope. The sky coverage is a 10° band centered on the ecliptic.

CHEN: Lunar occultation is indeed a powerful technique in the study of binaries, however I want to caution people on its use in diameter determinations. Most of the quoted errors are from least-squares solutions which tend to be optimistic. The main difficulty comes from the lack of precisely known point-source responses. Systematic errors, such as the uncertainty of the lunar limb slope or the spectral shape within a given bandpass, can be much larger.

WHITE: The formal error of least–squares fits measures random noise. It does not provide strong indication of systematic problems. Like many observing techniques, when they are pressed to their limits, as in the observation I showed, the formal errors may be very optimistic.

SZABADOS: Have you tried the application of the occultation technique using planets instead of the moon?

WHITE: Not with the purpose of analysis. Other groups have such as that of Elliot and his colleagues at MIT.

BATTEN: Occultations by asteroids are now exciting as much interest as occultations of asteroids.

WHITE: A program of observing occultations by asteroids with portable telescopes has been successfully pursued for nearly a decade at the Lowell Observatory under the direction of R. Millis.

McALISTER: Most of you probably do not know that Nat White is the Vice–Mayor of the city of Flagstaff, Arizona. He is missing his final city council meeting to attend this meeting, and so we see a rare example of science triumphant over politics!