2.1 INTRODUCTION

On a clear, dark night several thousand stars can be seen at any one time. They form familiar patterns such as the Great Bear and Cygnus in the northern hemisphere and Scorpio and Crux in the south. The distances are so great that we see the constellation patterns essentially unchanged from those seen by the Ancient Egyptians for instance. This is partly due to the fact that some of the bright stars in constellations are in what are called moving groups - a loose association of stars moving through space together. More tightly bound are clusters of star such as the Pleiades or 7 Sisters which appears in the northern sky in the late summer. Eventually the moving groups and clusters of stars will gradually disperse because the distance between the stars is such that the gravitational attraction between the members is relatively weak.

Those with keen eyes will be able to see some close pairs of stars without optical aid. The most famous is Mizar and Alcor in the tail of the Great Bear. The first recorded 'naked-eye' pair is ? Sgr which was mentioned by Claudius Ptolemy in his famous Almagest catalogue of circa 140 AD. It is described (1) as 'The star in the middle of the eye (of Sagittarius) which is nebulous and double'. The angular separation of this pair is 13 arc minutes, or about the same separation as Mizar and Alcor. As a comparison, the apparent diameter of the Full Moon is 30 arc minutes.

2.2 RELATIVE POSITIONS IN VISUAL DOUBLE STARS

The separation is one of two quantities needed to fully describe the relative position of double stars, the other being the position angle. With the brighter of the two stars being taken as the origin, the separation is defined as the angular distance in arc seconds between the two stars and the position angle is the bearing of the fainter star from the brighter in degrees with north being taken as 0 degrees, E is 90 degrees and so on (Fig 1.1a shows the situation for the naked eye and binoculars). When a telescope is used the view is inverted so Fig 1.1b applies to telescopic views.)

Fig 1.1a Naked eye and binoculars Fig 1.1b Telescopic view

It is usual to represent separation by the Greek letter rho (ρ) and position angle by the Greek letter theta (θ). These terms will be used throughout this book. Another common term is Δm which is shorthand for difference of magnitude between the primary and secondary stars. Unless otherwise stated the magnitudes in this book will be visual. The fainter of the two stars is sometimes called the comes, a Latin word meaning companion.

2.3 NAKED EYE LIMITS

In the case of the human eye, the closest pair of stars which can be seen unaided depends on the diameter of the pupil. This, in turn, depends on the lighting conditions and when fully dark-adapted the pupil may be 6 or 7mm in diameter, suggesting that the limit of resolution from the Airy formula (see Chapter 10) is about 20 arc seconds but the presence of aberrations in the eye and the low light levels from the night sky conspire to reduce the effective resolution to about 2.5 arc minutes.

In practice a normal pair of eyes should be able to see the stars θ^1 and θ^2 Tauri at 5.5 arc minutes without difficulty and some may be able to make out ϵ^1 and ϵ^2 Lyrae at 3.6 arc minutes, greatly. Ability to resolve naked-eye pairs tends to deteriorate with age and younger eyes will probably do better, although practice undoubtedly enhances keenness of vision. Sight, like hearing, or any of the five senses, can be improved with experience .Table 1 contains a short list of bright wide, pairs which, it is suggested, can be used as a test of naked eye resolving power. In some of the cases, both stars have a Bayer letter or Flamsteed number and these are used as the main identifier. The positions are given for equinox 2000.0 followed by the date of the most recent measure, the visual magnitudes of both stars and the position angle and separation of the pair. Most of these pairs are the results of chance alignment.

2.4 OPTICAL PAIRS

Optical double stars are simply formed due to line-of-sight coincidence. They are usually widely separated ($>$ 5 arc seconds or so) and the proper motions, or the individual motions in right ascension and declination, of each component, across the sky, are significantly different. In addition, the stars are usually unequally bright reflecting the difference in distances but this by itself is not a criterion. A good example is δ Herculis where the two stars were separated more than 34at discovery by the elder Herschel in 1779, they closed up to about 8.8 in 1964 and are now at 12and widening (Fig 1.2a). Such pairs are usually of no direct scientific interest to astronomers but can produce some fine sights in small telescopes. The stars in δ Herculis are, for instance, pale yellow and blue in colour and the primary is about 24 parsecs distant. Little is known about the companion.

Fig 1.2a The proper motion of δ Herculis. Measurements of the position angle and separation of star B with respect to A over many years shows the relative motion between the two. Fig 1.2b shows the real situation with star A moving towards PA 187at a rate of 0.159 per year whilst B moves towards PA 275by 0.117 per year.

Table 1.1 Some naked-eye double stars

2.5 TELESCOPIC PAIRS

Whilst binoculars, particularly the image-stabilised variety (see Chapter 3) can show literally hundreds of double stars the use of a small telescope will considerably increase the number of pairs of stars that can be seen. It also allows the user to see stellar colours more easily. In a 90-mm telescope, most of the closest pairs than can be seen are binary pairs - the two stars are physically connected by a mutual gravitational bond - and they rotate around the common centre of gravity in periods ranging from a few tens to a few millions of years.

Table 2.1: Some naked-eye double stars

RA 2000 Dec 2000	Pair	Epoch	PA ()	Sep ()	Va	Vb
0318.2 -6230	ζ Ret	2003	217	309.2	5.24	5.33
0425.4 +2218	κ Tau	2002	174	339.7	4.21	5.27
0428.7 +1552	θ Tau	2002	348	336.7	3.40	3.84
0439.3 +1555	σ Tau	2008	194	436.3	4.67	5.08
0718.3 -3644	Jc 10 Pup	1997	98	240.1	4.65	5.11
1208.4 -5043	δ Cen	1999	325	269.1	2.58	4.46
1450.9 -1603	α Lib	2002	315	231.1	2.75	5.15
1622.4 +3348	ν CrB	1998	164	360.8	5.20	5.39
1844.3 +3940	ϵ Lyr	2009	172	219.2	4.59	4.67
1928.7 +2440	6 -8 Vul	2008	28	427.3	4.44	5.82
2013.6 +4644	31+32 Cyg	2008	325	333.8	3.80	4.80
2018.1 -1233	α Cap	2002	292	381.2	3.80	4.20

2.6 BINARY STARS

2.6.1 Visual binaries

In the case of physically connected pairs of stars what the observer sees when he plots the position angle and separation of the pair over a number of years is a curve. If followed for the whole orbital period the result would be an ellipse - this is the apparent orbit, in other words, the projection of the true orbit onto the plane of the sky. With a small telescope, hundreds of binary stars can be observed and of these the more nearby pairs offer the best chance of seeing the orbital motion over a few years. Estimates of separation can be made in terms of the diameter of the apparent disk of the brighter component which can be calculated for any telescope aperture using the Airy formula in Chapter 10. Position angle can be estimated to perhaps the nearest 5 or 10 degrees by eye by allowing the pair in question to drift through the field at high magnification with the driving motor stopped.

True (and apparent) orbits come in all shapes and sizes from circular to elongated ellipse but the tilt of the orbital plane can also vary from 90 degrees (in which the plane is in the line of sight) to 0 degrees in which we see the orbit face-on. To describe the real orbit fully requires 7 quantities of which eccentricity and inclination have just been explained. In the ellipse, the time at which the two stars are closest is called periastron (similar to perihelion when the Earth is nearest the Sun). The other values are the orbital period in years (the time taken between successive arrivals by star B at the periastron point and three values which describe the size and orientation of the orbit which are described fully in Chapter 7. The motion of star B around A follows Kepler's Laws and in an exact analogy with the solar system, the mass of both stars is related to the size of the orbit and the orbital period.

Fig 1.3a The visual binary 12 Lyncis. p = 706 years, e = 0.03 and orbit inclined at 2to the plane of the sky. Fig 1.3b - γ Virginis, P = 169 years, eccentricity = 0.89, inclined at 32to the plane of the sky. The radius of the central circle indicates the Dawes limit for a 20-cm aperture. 12 Lyncis is therefore always visible in this aperture. γ Virginis closed to less than 0.4 in early 2005 but is now widening rapidly and will need only 8 to 10-cm for the forseeable future.

Fig. 1.3 gives an example of two well-known visual binaries. Contrast the orbital motion in both pairs by comparing the positions at 1950, 2000 and 2050.

To measure the total mass of both stars requires the apparent orbit to be defined as accurately as possible. This can be done by measuring ρ and θ at different times, for as much of the orbit as is practical. (Long periods will mean that only a preliminary orbit can be obtained). There are measuring techniques of various kinds which can be employed to accurately measure the relative position of B and to determine the values of ρ and θ. Later in this book the various methods that are available to the observer are mentioned in more detail.

For visual binaries, observations of the apparent orbit leads to the determination of the true orbit from which we can derive the sum of the masses, in terms of the solar mass, provided that the parallax is known. The astrometric satellite Hipparcos has been instrumental in providing parallaxes of high accuracy for a large number of binary stars.

Once we know the apparent orbit of a visual binary, we can, if the parallax of the system is also known, obtain the sum of the masses of the stars in the system via Kepler's third law:

where a is the semi-major axis of the apparent ellipse, and π is the parallax. Both are in arc seconds and P is in years. The mass sum is then given in units of the sun's mass.

To obtain the individual masses requires defining the apparent orbit for each component by measuring its position with time against the background field stars. The apparent orbits are identical with the relative sizes determining the ratio of the masses, the primary star being the most massive, traces out the smaller ellipse (see Fig 7.1). Unfortunately this method only applies to a small number of wide, nearby pairs which can be resolved photographically throughout the orbit.

Combining (1.1) and (1.2) allows us to get the mass of each component.

The USNO 6th Catalogue of Orbits(2) contains more than 1,xxx orbits of which 1,xxx refer to pairs resolvable by conventional techniques. Of these orbits, about 4grade 1, the longest period being that of 70 Oph at 88.38 years. Table 1 shows the distribution of the 5 main orbit grades (Sept 2010). Throughout this volume reference will be made to the 5th and 6th editions of this catalogue. The 5th edition is available from the USNO on CD-ROM ? (see the appendix) whilst the 6th is the dynamic version which is regularly updated but a copy of this version appears on the CD-ROM accompanying this book.

Table 2.2: Distribution of orbit quality in the USNO Sixth Orbit Catalogue

Grade Category	Longest period	No. pairs	% of catalogue
Definitive	88.38	61	3.6
Good	206	238	14.1
Reliable	540	370	21.9
Preliminary	4277	527	31.1
Indeterminate	6675	497	29.3

2.6.2 Spectroscopic binaries

These are stars which appear single in all telescopes but turn a spectroscope on them and the spectral lines are observed to shift periodically with time due to the Doppler shift as the stars approach and then recede from the observer. The lines merge when the stars are both moving across the line of sight. There are two main types. When the stars are of similar brightness then two sets of spectral lines can be seen particularly when one star is moving towards us and the other is moving away. These are called double-lined systems. When one star is much brighter than the other then only the spectral lines the bright star can be seen to move periodically. This is called a single-lined system. Spectroscopic binaries have periods ranging from hours to a few tens of years. In a few rare cases they can also be resolved using speckle or ground -based interferometry. Such systems are important as they allow many characteristics of the component stars to be determined.

2.6.3 Astrometric binaries

Again, these are single objects in all telescopes but reveal their duplicity by the effect that the unseen companion star has on the proper motion or the transverse motion of the star against the background of fainter stars. This motion will be constant for a single star but the presence of a companion constantly pulls on the primary star and the effect is to observe the star 'wobble' across the sky . This was first noticed by Bessel in the proper motion of Sirius - some 3.7 arc seconds every year and large enough to be seen by regular measurement with respect to the neighbouring stars. Bessel rightly attributed the periodic wobble of Sirius to the presence of an invisible but massive companion. In 1862 Alvan Clark saw Sirius B for the first time thus confirming Bessel's prediction.

2.7 MULTIPLE STARS

Less common in the telescope, but more spectacular and worth seeking out are the multiple stars. Systems like β Mon, with its 3 pure-white gems within 7 arc seconds, ζ Cancri, of which more later, and ι Cas (yellowish, bluish and bluish, according to Robert Burnham).

If multiple stars are to be stable over a long timescale then they need to follow a certain hierarchy. In the case of a single star orbiting a close pair, the ratio of the orbital periods of the outer star around AB to that of the inner orbit AB is usually at least 10:1. This appears to apply from periods of about 10 days up to thousand of years.

Quadruple stars, of which the most famous is the 'double-double', epsilon Lyrae can be ordered in two ways. Firstly, as in epsilon's case, there are two pairs each orbiting the common centre of gravity. Alternatively, a double star is orbited by a distant 3rd star and then even more distantly a fourth star circles the whole group.

Systems of higher multiplicity are known - perhaps the most famous is the sextuple system Castor, which is described in more detail in Chapter 9. A recent catalogue of multiple stars(3) lists 626 triples, 141 quadruples, 28 quintuples and 10 sextuples. The existence of two systems thought to be septuple (? Scorpii and AR Cas) awaits confirmation of further suspected components.

The Trapezium, which to a small telescope user is four stars embedded in the Orion Nebula, is the prototype of another sort of multiple star. It is not strictly ordered like the quadruples such as epsilon Lyrae, but is more a loose aggregation and can be regarded more as a small star cluster than a multiple star as such. It is not any the less beautiful for this and seen against the glowing green background of the nebula, on a cold winter's night in a good telescope it is one of the sky's most spectacular sights.

2.8 HISTORY OF DOUBLE STAR OBSERVATION

In 1610 the invention of the telescope by Galileo gradually led to the discovery of telescopic double stars but these were noted merely by the way. In 1617 Castelli found that Mizar was itself double(4) and he later added a few more pairs. In 1664 Robert Hooke was observing the comet discovered by Hevelius when he came across γ Arietis, a pair of pure-white stars of the 4th magnitude separated by some 8 arc seconds.

Over the next one hundred years or so a few more double stars were noted but not catalogued in any determined manner, but this was to change when the Reverend John Michell first suggested that double stars were not merely a line-of-sight effect but that the two components really revolved around each other under a mutual gravitational influence, implying that Newton's Laws applied to objects outside the Solar System. In Philosophical Transactions for 1767, Michell says " ... it is highly probable in particular, and next to a certainty in general, that such double stars, &c, as appear to consist of two or more stars placed close together, do really consist of stars placed near together, and under the influence of some general law, whenever the probability is very great, that there would not have been any such stars near together, if all those that are not less bright than themselves had been scattered at random throughout the whole heavens".

A small catalogue of double stars was compiled in 1780 by Christian Mayer of Mannheim (5) but the next great step was taken by William Herschel who turned his unprecedently powerful telescopes on many bright stars to find that even at

Table 2.3: The first ten telescopic double star discoveries

Pair	Discovery	By
ζ UMa	1617 Jan	Castelli
β Mon	1617 Jan 30	Castelli
θ Orionis ABC	1617 Feb	Galileo
β Sco	1627	Castelli
γ Ari	1664	Hooke
Castor	1678?	G. D. Cassini?
ζCnc AB-C	1680 Mar 22	Flamsteed
α Crucis	1685	Fontenay
α Centauri	1689	Richaud
γ Virginis	1718	Bradley

high power, some stars appeared as very close pairs. In an attempt to measure stellar parallax, Herschel argued that in unequally bright, close pairs by measuring the position of the faint (hence distant and fixed) star with respect to the bright (or nearby) star he should be able to measure the parallactic shift and hence the distance of the latter. This idea he attributes to Galileo. To prove this he used filar micrometers of his own construction to measure the position of the fainter star with respect to the brighter. However, instead of seeing a 6 monthly 'wobble' in the position of the bright star with respect to the faint, Herschel found that the relative motion between the two stars was curved and could only be explained if the stars were revolving around a common centre-of-gravity. He had proved that binary stars existed but the mathematical confirmation came six years after his death, in 1828, when the French scientist Savary used the pair ξ UMa (which Herschel had discovered) to show that the apparent orbit of the fainter star around the brighter (assuming the latter was fixed) was an ellipse.

The significance of this work was that it gave an estimate for the ratio of the stellar masses in a binary star system. This resulted in a great impetus in the visual observation of double stars and over the next 50 years or so many rich amateur astronomers in Europe dedicated time and money to making micrometric measurements, or paying someone to do it for them. Dawes, in England, and particularly Baron Ercole Dembowski, in Italy, and others flourished but without the excitement of discovery the work lost momentum and became largely unfashionable by the turn of the century.

In 1857 when Bond first imaged Mizar with the Harvard 15-inch refractor the advantages of photography for double star astronomy were not immediately realised, partly because the resolution obtained initially did not allow much work to be done in the orbital pairs of relatively short period. For those bright pairs where the separation was such that both components could be imaged at all parts of the orbital cycle such as 70 Oph, it was possible to determine individual masses from the size of the apparent ellipses that each star traced out against the stellar background. It was not until the middle of the last century that observers such as Willem Luyten, Peter van de Kamp and Wulff Heintz used photography much more purposefully. Luyten, in a long career, found many pairs of stars with common proper motion, indicative of orbital pairs but with a long period. van de Kamp concentrated on those systems where the only evidence of duplicity was a periodic wobble of a bright star with respect to the background, indicating a faint and close but nonetheless significantly massive companion star.

2.9 THE GREAT ERA OF DISCOVERY

From 1870 or so when the American astronomer S. W. Burnham first started in double star astronomy a golden period for discovery opened up and continued for about 80 years, first in the northern hemisphere and latterly in the south. The largest refractors in existence were used in systematic surveys of the BD star catalogues by R. G. Aitken and W. J. Hussey in California (they discovered 4,700 pairs between them) and some years later by R. T. A. Innes, W.H. van den Bos and W. S. Finsen at the Republic Observatory, Johannesburg (5,000 discoveries) and Rossiter and colleagues at the Lamont-Hussey Observatory at Bloemfontein (7,650 discoveries) in South Africa. When the latter retired in 1952 it was not long before P. Couteau and P. Muller in France began to search for new pairs again, dividing up the northern heavens with Couteau tackling the zones from +17to +52and Muller surveyed the zones near the north pole. They were remarkably successful and Couteau's list now exceeds 2700 new pairs whilst Muller found more than 700. Additionally, W. D. Heintz found 900 new pairs, most of them in a zone close to the equator and in the southern hemisphere.

2.10 MODERN TECHNIQUES

Although it was proposed by Albert Michelson almost a hundred years ago, stellar interferometry is today even more important as a means of researching the dynamics of binary stars as it was then. Michelson's idea led to the construction of an interferometer for the 100-inch reflector on Mount Wilson in the 1920's, consisting of a 20-foot structure with flat mirrors at each end mounted at the top end of the telescope tube.

This instrument uses the interference of light to determine whether a bright single star is either extended i.e. its diameter is resolvable at the Earth or a close double. By combining the light from each of the two small mirrors and adjusting the separation of the mirrors until the fringes thus formed combined in such a way that they cancelled each other out then the separation of the two components could be found from the separation and the position angle from orientation of the fringes. With so little light available only bright stars could be measured.

In 1925 Frederick Pease(6) first resolved Mizar A using this equipment. It was also used for observations of extended sources such as the red supergiant Betelgeuse meant that the diameter of the star could be determined. Other stars measured included the binary system Capella which turned out to have a separation of between 0.03 and 0.05 arc seconds and a period of 104 days.

In the 1970's double star observation underwent a revolution with the invention of speckle interferometry (see Chapter xx). This technique effectively removes the effect of the atmosphere and allows telescopes to operate to the diffraction limit. In the case of the 4-metre reflectors on which it was used, this corresponded to about 0.025 or about 4 times closer that Burnham or Aitken could measure. In addition the accuracy of this method was much greater than visual measures and since then it has proved its worth by discovering new very close and rapid binaries and improving the older visual orbits.

The launch of the Hipparcos satellite in 1989 also heralded a new era of double star discovery. Operating high above the atmosphere its slit detectors found some 15,000 new pairs, most of which are difficult objects for small telescopes but a number have already been picked up in very small apertures.

2.11 THE FUTURE

Where does double-star observation go next? In the immediate future it will be from the ground where a number of specially-built optical arrays will be operating over the next few years.

At Cambridge in the UK, the COAST (Cambridge Optical Aperture Synthesis Telescope) 5 mirror interferometer has been working for some years with a current baseline of 48 metres and plans to extend this to 100 metres. This is an extension of the Michelson instrument at Mount Wilson. By using more mirrors and using the Earth?s spin to rotate the instrument with respect to the star astronomers have used phase closure, a technique first used in radio astronomy, to effectively image the structure of stars such as Betelgeuse.

It has easily resolved the bright spectroscopic binary Capella, whose components are about 50 mas apart. Another such instrument, the NPOI (Navy Prototype Optical Interferometer) using 50 metre baselines in Arizona has resolved spectroscopic binaries such as the brighter component of Mizar. Long-known to have a period of 20.5 days, the NPOI can detect and measure the individual stars even though at closest approach they are only 4 milliarcseconds (mas) apart (see Fig 9.1). The combination of the NPOI data and the spectroscopic data can give very accurate values for the size of the orbit, the parallax of the system and the individual masses, and radii of each component.

Soon the CHARA (Centre for High Resolution Astronomy, Georgia State University) array in Arizona which employs 1-metre telescopes will be operating with a 350-metre baseline and the Sydney Univerity Stellar Interferometer instrument (SUSI), currently working at a baseline of 80 metres is eventually planned to operate at 640 metres. This will ultimately give a resolution of 75 microarcseconds (0".000075) and will allow binaries with periods of hours to be observed directly.

Peter Lawson's website(7) covers all the current interferometer projects and has links to the historical ones.

The greatest contribution to the discivery of ew binary stars will come from space. The Hipparcos satellite discovered x,ooo new visual pairs down to separations of about 0/as.1, and a number of astrometric binaries but the planned GAIA mission, which is not due to fly until about 201x is expected to find tens of millions of new double stars. For the resolved pairs, the magnitude difference is important. Equally bright pairs (¡15th mag) will probably be (completely resolved at 10 mas, while a 20th magnitude companion would be seen only at some 50 mas. Closer pairs will be observed by their photocentres, but in the 'favourable' period-range 1-10 years, a large proportion of them will have their astrometric orbits determined. This will be possible for photocentric orbit-sizes below 1mas, at least for the brighter systems. Bright (again <15th mag.) shorter-period systems (days/months) will be observed by the radial-velocity instrument (at 0.1 mas separation), and millions of (mainly even shorter-period) eclipsing binaries will be observed photometrically.

2.12 REFERENCES

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