INTRODUCTION

This new edition of the *Cambridge Double Star Atlas* is designed to improve its utility for amateur astronomers of all skill levels.

For the first time in a publication of this type, the focus is squarely on double stars as *physical systems*, so far as these can be identified with existing data. Using the procedures described in Appendix A, the target list of double stars has been increased to 2,500 systems by adding 1,100 “high probability” physical double and multiple stars and deleting more than 850 systems beyond the reach of amateur telescopes or lacking any evidence of a physical connection. Wil Tirion has completely relabeled the *Atlas* charts to reflect these changes, and left in place the previous edition’s double star icons as a basis for comparison. This new edition provides a selection based on evidence rather than traditional opinion, so that the twenty-first century astronomer can explore with fresh eyes the astonishing actual variety in double stars.

Continuing the emphasis on physical systems, this *Atlas* explains the origin and dynamic properties of double stars and the role they have played in our understanding of star formation and stellar evolution. The elements of binary orbits, stellar spectral types, and methods of detecting and cataloging double stars, are explained to enrich the observer’s understanding of double star astronomy. There is also practical guidance for the visual astronomer – information on optics, equipment preparation, useful accessories, viewing techniques and opportunities for amateur research. The references suggest both print and online double star resources. Finally, over 330 systems in the target list are marked with a star (★) in the left margin. These indicate “showpiece” systems of intrinsic beauty or charm, “challenge” pairs of close separation or large brightness contrast, and several systems that have been important in the history of astronomy. From most observing locations, at least three dozen of these targets will be in view at any time of night on any evening of the year.

Jim Mullaney’s choice of nineteenth century double star catalog labels has been retained as a tribute both to his original *Atlas* concept and to the bygone astral explorers who discovered over 90% of the systems in the target list (see Appendix D). These labels are also a convenient link to the legacy double star literature and a compact labeling style for the *Atlas* charts. However, as a convenience to the digital astronomer, the target list provides both the Henry Draper (HD) and Smithsonian (SAO) catalog numbers for each system. The first will identify each system in the research literature and online astronomical databases, the second is a compact targeting command or search keyword recognized by most GoTo telescope mounts and planetarium software.

What are double stars?

Let’s start by adapting the definition from double star astronomer Wulff Heintz:

> A double star is two or more stars that are bound by mutual gravitational attraction into an enduring (usually lifelong) dynamic system.

The fundamental unit is two stars – usually termed a *binary star* – orbiting their mutual center of gravity. But a double star may also be triple, quadruple, quintuple and so on, under the umbrella category of *multiple star*. Using the singular *star* indicates that a binary or multiple star is a single physical system, an astrophysical fact. By contrast, an *optical double star* is (as the name implies) only an optical illusion, two stars far apart in space that appear side by side on the illusory celestial sphere. Although in most cases evidence for physicality is inconclusive or entirely lacking, especially in distant pairs, advances in astronomy in recent decades have given us a new capability to distinguish fact from illusion in double star astronomy.

Double stars display an enormous range of orbital dynamics and stellar types, and produce characteristic visual patterns that the astronomer will encounter often at the eyepiece. The most common of these patterns are illustrated on the back cover. The challenge for double star astronomers is to understand how these systems were formed and how they will change over time, then to apply this knowledge to answer basic questions about our Galaxy.

Remarkably, all evidence suggests that most if not all stars in the Galaxy were formed as members of double star systems. This means that nearly all the double stars we observe have been united from birth. And most double stars will eventually die together, one after the other, like Romeo and Juliet. We know this from the many binary systems that contain a dead or dying star, and the large number of binaries that are orbiting so closely they can never be torn apart.

The old view was that double stars formed by randomly falling into mutual orbits as they circled the Galaxy, or appeared when a single massive star rotated so rapidly that it split in two. The current view is that double stars are literally born together from a single *cloud core* of gas and dust collapsing into its own gravity. The collapsing core, stressed by external shock waves and internal turbulence, divides into two or more protostars (*prompt fragmentation*). Matter that continues to fall toward a protostar swirls into an enormous accretion disk that often develops spiral arms or irregular clumps (*disk fragmentation*). These also gather mass to become low mass companion stars or planetary systems.

These collapsing cloud cores rarely form in isolation: most are found inside a much larger concentration of gas and dust known as a *star forming region* (SFR). The number of stars that form within a single SFR depends on the mass, density and turbulence of the gas and dust it contains, but a typical SFR can span tens of parsecs and produce hundreds or thousands of new stars. Inside these murky clouds, usually found churning along the arc of a galaxy spiral arm, protostars attract matter and grow hotter and more compact with the increasing pressure of gravitational contraction. Within a few million years at most, the most massive of these young stars fire up their thermonuclear cores, push back the clouds with the force of their radiation, light up the dispersing gas as an emission nebula, and unveil a young star cluster to our view.

The masses, rotational speeds and orbits of double protostars depend on the turbulence of the cloud core, the density of gas and dust in the SFR, the rate of their mass accretion and the angular momentum inherited from their accretion disks. They also depend on interactions with other stars in their cloud core and natal star cluster. Binary protostars are slowed into smaller orbits by friction with their enveloping clouds; as they grow in mass, near encounters with other stars in the natal cluster can shear apart widely separated or "soft" companions, perturb stable orbits, and bind tighter already close orbiting or "hard" binaries. The often elliptical shape of double star orbits and the extreme variation in orbital periods are the result of these cumulative influences. Even stars too far apart to have formed in the same cloud core can display *common proper motion* – parallel motion across the sky – because they were born in the same SFR and escaped in the same direction as the natal cluster dissolved. For all these reasons, double stars have been called the "fossils of star formation."

How stars form is only one of the many mysteries that double stars have illuminated in the history of astronomy. William Herschel discovered in 1802 that they moved in orbits, demonstrating that Isaac Newton's gravitational attraction governed not just our solar system but the visible universe. In the nineteenth century, systematic discovery and observation of nearby binary systems led to refined methods of measurement and orbital calculation, which allowed astronomers to "weigh" double stars and discover the enormous range in stellar masses. With accurate estimates of stellar distance from the parallax surveys of the twentieth century, mass could be compared to intrinsic brightness (*absolute magnitude*). This confirmed that the brightest stars are also the most massive and pointed to nuclear fusion as the only possible source of starlight; theoretical physics could then deduce the paths of stellar evolution. Double stars have also been essential to our understanding of star clusters, many types of variable stars, supernovae, black holes and exotic high energy sources in deep space. They are the keystone species of the Galaxy.

What are double stars? The astronomer Simon Portegies Zwart answered the question this way:

Binaries are the basic building blocks of the Milky Way as galaxies are the building blocks of the universe. In the absence of binaries many astrophysical phenomena would not exist and the Galaxy would look completely different over the entire spectral range.

The binary orbit

The essence of double stars is found in the binary orbit, which is a stable dynamic balance between mutual gravitational attraction and centrifugal orbital energy.

Let's start with the simplest example of two identical stars in a circular orbit. (Circular orbits are often found in close binaries that orbit in 10 days or less.) Each star attracts the other, so the total gravitational attraction between the two stars is proportional to their combined *system mass* ($M_1 + M_2$). But the strength of their mutual attraction varies as the *inverse square* of the distance between the stars. If the distance is multiplied by a number, the gravitational attraction is reduced by the reciprocal of the number squared. Increasing the distance by three times reduces the gravitational attraction to 1/9; reducing the distance by half increases the gravitational attraction four times.

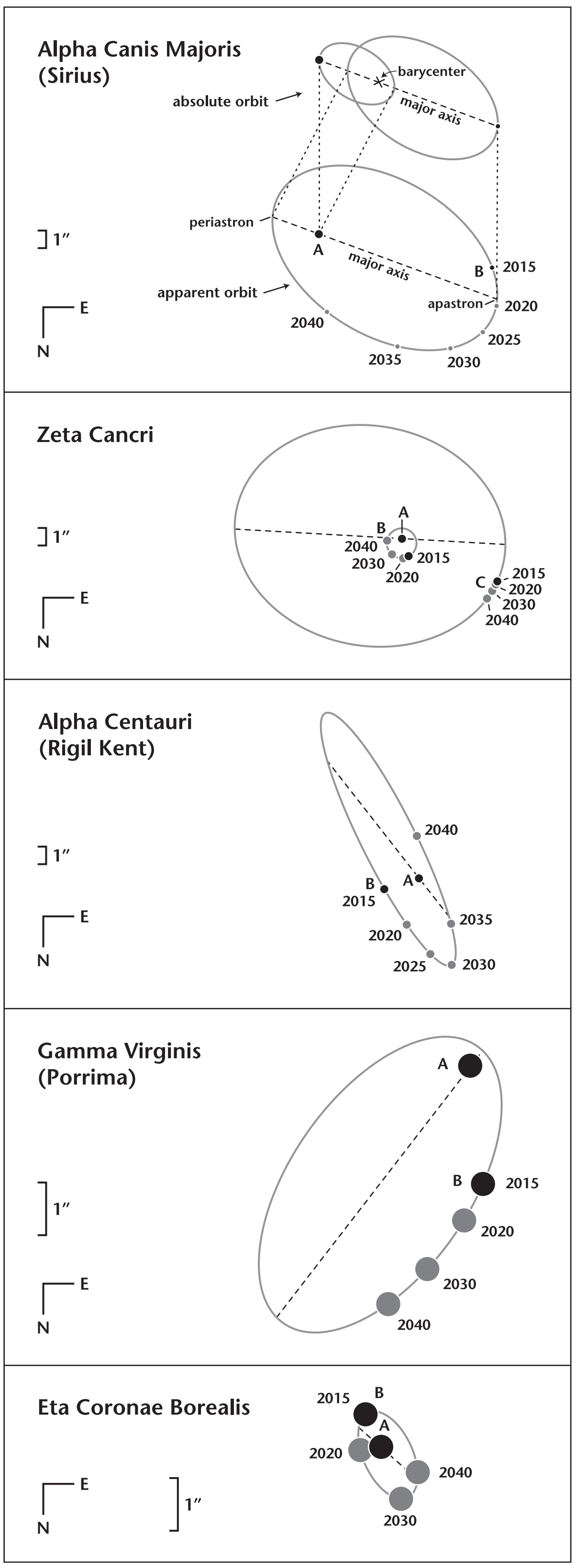
In a circular binary the nominal *orbital radius* (r) is the distance from one star to the other, but each star actually orbits their common center of mass or *barycenter*, at the center of their shared circular orbit. The two stars are always connected by a line through this fulcrum point, which means they have the same *orbital period* (P). As the stars revolve around the barycenter, their constant gravitational attraction is offset by a constant orbital velocity. A greater system mass or smaller orbital distance would require a greater orbital velocity to offset the greater gravitational attraction.

This simplest of all possible binary orbits can be imbalanced in two ways. First, the two stars are usually of unequal mass. In that case, balance is restored by making the distance of each star from the barycenter proportional to the *mass ratio* (q), the mass of the smaller star divided by the mass of the larger (M_2/M_1). Like unequal weights on a balance beam, balance requires the larger star to be closer to the center of gravity. As a result, the heavier star moves in a separate circular orbit inside the orbit of the less massive star, and because its orbit is smaller, its orbital velocity is proportionally less.

Second, the distance between the stars oscillates in synchrony with the orbital period, from a point of closest approach (*periastron*) to a point of farthest separation (*apastron*). This sends the stars into opposing elliptical orbits around the barycenter, now located at one focus of each ellipse (see Figure 1, top). The two stars are still connected by a line through the barycenter, the orbits have the same elliptical elongation or *eccentricity* (e) (see Appendix B) and the larger star still moves at a lower average velocity in a proportionately smaller orbit. Because the mutual gravitational attraction increases as the mutual distance from the barycenter decreases, the changing distance between the stars must be balanced by a changing orbital velocity, reaching peak velocity at periastron, lowest velocity at apastron. This elegant combination of system mass, mass ratio, orbital radius, eccentricity and orbital velocity around the barycenter is the *absolute orbit*, the actual physical motions of a binary star (see Figure 1, top).

Unfortunately, the barycenter of a binary system is invisible to an observer, so it cannot be used as a reference point to measure the orbital motion. Instead, the brighter and usually more massive *primary star* is made the anchor point, and the motion of the fainter, less massive *secondary star* is measured in relation to it (see Figure 4). This is the *relative orbit.* It has the same period and eccentricity as the absolute orbit, but now the average orbital radius (r) is equal to the *semi-major axis* (a), half the longest dimension of the orbital ellipse. (Half the shortest dimension is the *semi-minor axis*, b.)

As a final wrinkle, the relative binary orbit is almost always tilted to our direction of view. This will make a circular orbit appear elliptical, like the rim of a cup viewed from one side, and the point of periastron in an elliptical orbit may not be the point of smallest visual separation between the two stars (see alpha Centauri in Figure 1). This *apparent orbit* is what we actually observe and measure on the celestial sphere. Complex mathematics, applied to painstaking observations of position and orbital velocity over decades or even centuries, are required to derive the



dimensions of the relative orbit and the dynamics of the absolute orbit from the distorted path of the apparent orbit.

The balance in a binary orbit between gravitational attraction and orbital energy is summarized in a proportion known as Kepler's third law. This is easiest to calculate if we measure system mass in units of *solar mass* (1 $M_\odot$ is the mass of the Sun), orbital radius in *astronomical units* (1 AU is the distance from the Earth to the Sun) and period in *Earth years.* Then Kepler's third law is simply:

$$(M_1 + M_2) = r^3/P^2$$

The target list indicates both the period (P) and average orbital radius (r) for all systems with an orbital solution. For these, you can use Kepler's third law to calculate the system mass.

If we don't know the orbital radius, but know the distance (d) to the double star in parsecs (denoted pc; one parsec is equal to 206,265 AU or 3.26 light years) and have measured the angular separation (ρ or *rho*) between the stars in arcseconds, then the *projected separation* (ps) between the stars, again in astronomical units, is:

$$\text{ps} = \rho \cdot d.$$

This is always a minimum separation, because a tilted (foreshortened) orbit will make the distance between stars appear smaller than it actually is.

Multiple star orbits

What happens in a system of three or more stars? Here a binary orbit still prevails, but in a remarkable way – it becomes enormously larger. This creates the defining feature of a stable multiple star: a *hierarchical orbit structure* (Figure 2).

A binary pair – the building block of every double star – is bound by mutual attraction to a common barycenter. If a third star approaches too close to this

Figure 1 – Five binary orbits
The absolute orbit of Sirius (top) shows the elliptical orbits of the two components around their mutual center of gravity. The five apparent orbits shown are the orbits we actually measure. The dotted line indicates the major axis of the relative orbit with apastron and periastron at opposite ends.The current (2015) position of the components is shown with their predicted future positions out to 2040. The diagrammed star disks match the Airy disk diameter produced by a 250 mm aperture.

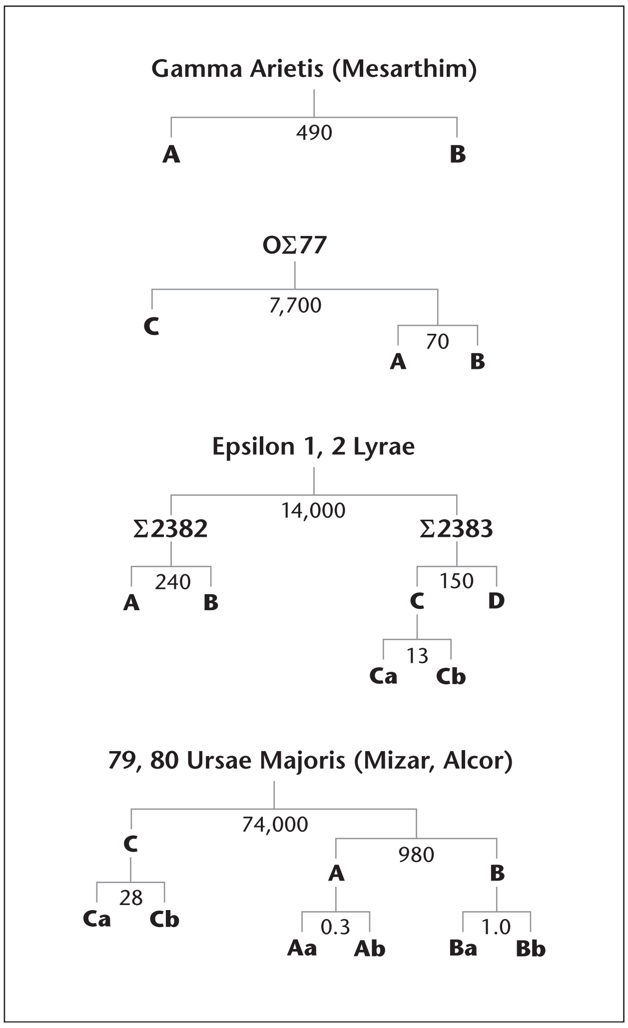


Figure 2 – Hierarchical multiple star orbits
Multiple stars are composed of binaries and single stars arranged in a hierarchy of orbits. The horizontal bars indicate the orbits, the number below each bar the orbital radius in astronomical units. Double stars of 2, 3, 5 and 6 components are drawn from the target list. The examples also show how multiple star components are labeled.

couple, the barycenter formed by all three stars becomes unstable and their orbits unpredictable. But a binary can join with another binary or single star if they partner at a much greater orbital distance, often 100 to 1,000 times the orbital radius of the binary. At this remove a binary influences the distant barycenter as if it were a single large star, and can form one half of a stable "binary" unit. From the inverse square principle, we see this can reduce to 1/1,000,000th the gravitational disruption that the third component might exert on the binary orbit. Yet this bond can still be strong enough to resist the attraction from other stars in the Galaxy, making the triple star an enduring dynamic system.

This hierarchical segregation of orbits distinguishes a multiple star from its natal star cluster. In the cluster, all the star systems orbit the single barycenter formed by the entire cluster, stars are deflected into new orbits each time they pass through the cluster, and "evaporation" (as dispersing gas and dust reduces the mass of the cluster, weakening the gravity that holds the cluster together) dissolves nearly all natal star clusters within a few 10 million years.

Multiple protostars seem to form within a single cloud core, so at birth they will have similar, dynamically unstable orbits. So how does a hierarchical structure develop? Through competition. As the protostars orbit their common center of gravity, by chance all three can approach periastron near the same time. When this happens the two most massive or closest stars can join forces with their greater mutual attraction and hurl the less massive or more distant third star into a larger, higher energy and higher velocity orbit; this transfer of orbital energy allows the dominant pair to settle into a tighter, lower energy orbit. This process can be repeated many times within a few million years, "hardening" the inner binary and eventually imparting an escape velocity to the third star, ejecting it from the system.

Although ejection is very likely, it isn't inevitable. There are over 270 examples of "2+1" systems in the target list – many of them an unresolved spectroscopic binary with a wide third component – that have found a stable dynamic configuration. The less common "1+2" systems (a binary orbiting a more massive primary star) and the even rarer "double double" (2+2) systems can evolve in the same way, binding the binary units more tightly while increasing the orbital radius to other components. A nearby example is the wide naked eye pair Mizar and Alcor in Ursa Major. Mizar is also a close telescopic double, forming a 2+1 triple system. In fact all three components are very close binaries, forming a sextuple system of hierarchically segregated orbits (Figure 2).

Similar quintuple and sextuple systems are rare (only 40 are found in the target list), and hierarchical structure seems to reach its limit in systems of about seven stars. Beyond that, the competition among

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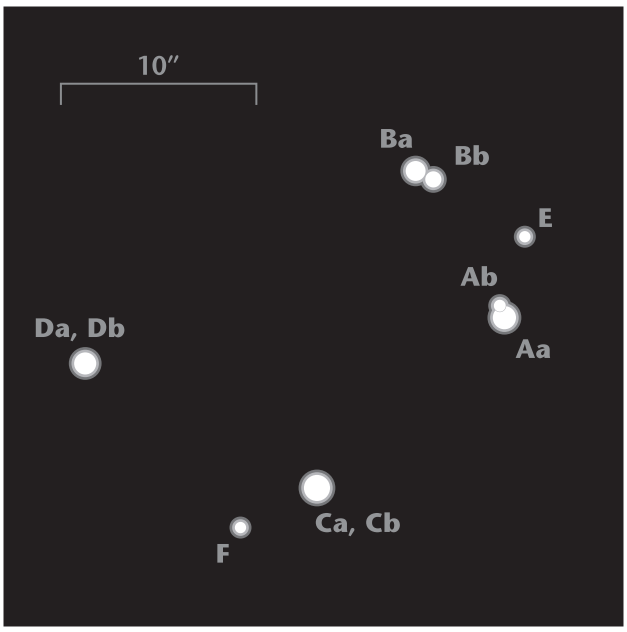

Figure 3 – The Trapezium in Orion
An unstable group of at least a dozen stars emerging from its natal cloud of gas and dust. Because the four brightest stars are competing to dominate their shared barycenter, the group is unstable and will eventually break apart.

components dissolves large stellar groups before they can develop a stable hierarchical arrangement. The 430 parsec far Trapezium, emerging from the Great Orion Nebula, is a case in point (Figure 3). A visual quartet where each of the four massive stars is already a binary or multiple system, there is no clear hierarchical ordering in their orbits or separations. Just a few million years old, this minicluster of a dozen or more stars already displays divergent motions, a sign that it is on the way to breaking apart.

Stellar mass and the binary life cycle

In stars, *mass is destiny*. The mass of a star determines how long it will live and how it will die. Because most binaries remain bound for the life of the component stars, this means mass determines the life cycle of the binary system as well.

A star is an enormous sphere of plasma, heated by the thermonuclear fusion of hydrogen or helium at its core. The fusion is ignited and contained by the enormous pressure of the star's mass, as gravity strives to collapse the star to a single point. The energy released by this fusion pushes the collapsing mass outward in all directions, stabilizing the contraction into a spherical body with an incandescent skin or *photosphere*. This shines with a peak energy or *effective temperature* and a characteristic brightness or *absolute magnitude* (*M*). As stars increase in mass they become much hotter and brighter, and the color of their light, the clue to their temperature, shifts from red to blue wavelengths.

This relationship between mass, color and brightness is indicated by a star's *spectral type*. For normal or *main sequence* stars, it is simplest to think in terms of four contrasting categories of stellar mass. (1) The hottest, brightest (and rarest) *high mass* O and B type stars, such as Mintaka, Rigel or Achernar, have a mass from 120 $M_{\odot}$ down to about 4 $M_{\odot}$, and shine with a brilliant, bluish light that includes vast amounts of invisible high energy ultraviolet and X-ray radiation. (2) Less massive *A type* stars, such as Sirius, Fomalhaut and Vega, are around 3 to 1.5 $M_{\odot}$ and the benchmark for a bright, "pure white" star color. (3) The *solar type* stars – F, G and larger K types, like the Sun, Procyon or Rigil Kent – are about 1.5 $M_{\odot}$ to 0.5 $M_{\odot}$ and peak in the visible spectrum with a pale to distinctly yellow light. (4) The coolest, faintest (and most numerous) *low mass* stars – smaller K and M types, such as 61 Cygni or Kruger 60 – are 0.5 $M_{\odot}$ or less and glow with a pronounced orange light that peaks in the invisible infrared (heat) and microwave wavelengths. Arranging these spectral types in order of decreasing mass and temperature yields the sequence O B A F G K M, traditionally memorized as *Oh Be A Fine Girl, Kiss Me*. Gradations within a type are indicated with a number from 0 to 9: for example, an A0 star has double the mass and triple the brightness of an A9.

All stars eventually consume the hydrogen available to their core, and once they do they leave the main sequence of normal stars. Solar and higher mass stars switch to fusing into carbon the core of helium "ash" that results from hydrogen fusion, and the resulting surge of new energy forces the surface of the star outward to 500 or more times its normal radius. This enormously expanded *giant* or *supergiant* surface area allows the photosphere to radiate vastly more light, making it perhaps 10,000 times brighter. The rarefied surface becomes cooler, shifting the peak wavelength into the infrared and giving old solar and high mass stars a similar bloated, bright and ruddy appearance. These developments are captured in the *luminosity type* of a star. A young or midlife, main sequence star is denoted with the Roman numeral V or IV; an expanding giant star by III; and a massive and massively expanded supergiant star – the most luminous star outside a nova or supernova – by Ia, Ib or II.

Due to the extreme heat in their massively compressed thermonuclear cores, high mass (O or B type) stars feverishly consume their reserves of fuel in a few tens of million years, while relatively cool, low mass (K or M type) stars can shine frugally for tens of billion years. In binaries of unequal mass ($q < 1.0$), the more massive component will enter the giant phase first, and this can create some spectacular stellar fireworks. In close binaries ($r <$ ~5 AU), the dying star may expand so far that it forms a *semi-detached binary*, transferring its remaining hydrogen to the companion and giving it a life-shortening greater mass. The donor star then collapses into an incredibly compact and hot carbon remnant called a *white dwarf*. When the companion also begins to die, it expands and pours hydrogen back onto the white dwarf via an encircling accretion disk, resulting in a Type Ia supernova or X-ray binary and, eventually, the sepulchre of a matched white dwarf binary.

Most binary orbits are too large for mass transfer to occur and the giant or supergiant phase unfolds in isolation. These "giant type" binaries are not uncommon among visual double stars (the target list includes almost 560). This is because the giant and its companion are both intrinsically bright, their high system mass can sustain large orbits that can be resolved at great distances, and the giant phase can last for a billion years.

Examples of the next stage – a main sequence star with a white dwarf companion – are harder to find, even in the solar neighborhood, because white dwarfs are very faint. The three best known examples, Sirius B (Figure 1), Procyon B and 40 Eridani B, are all within 5 parsecs of the Sun, yet Procyon's 11th magnitude (m.11) white dwarf can only be glimpsed in large telescopes.

The double star population

We now can address a basic question: what is the *multiplicity ratio*, the proportion of double stars among all star systems (whether single or double stars) in the Galaxy? In the solar neighborhood (within 25 parsecs of the Sun) and considering only average or *solar type stars* (F, G and more massive K types), recent research suggests the multiplicity ratio follows a "60%–60%" allocation: *Roughly 60% of individual stars are actually members of double or multiple star systems, but roughly 60% of star systems – those individual points of light in the sky – are single stars*. The corollary to this 60%–60% rule is: *About 70% of double stars are binary*. Among the roughly 40% of local, solar type star systems identified as double stars, 72% have only two components, 21% have three, 5% have four and only 2% contain five or more components.

This 60%–60% rule is not universal because mass strongly affects the multiplicity ratio. High mass (O and B type) stars have a multiplicity ratio of 80% up to perhaps 100%. In low mass stars – small K type, M type and even smaller brown dwarfs – the multiplicity ratio is apparently less than 30%. Equal mass binaries (q =1.0) seem more common in closely orbiting pairs, as components in multiple systems, and in low mass systems; unequal mass ratios ($q < 1.0$) are about equally common down to mass ratios of 0.2. Delving the extreme mass ratios, the vast majority of solar type stars, single or double, appear to support planetary systems.

The size of binary orbits, like the mass of stars themselves, covers an enormous range (see Appendix C). The closest orbiting binaries have been studied as *eclipsing variable stars*, apparently single stars that display a periodic and revealing variation in brightness as one star passes in front of the other. Some of these are contact binaries (W Ursae Majoris type variable stars), solar mass stars that circle each other in less than a day and are enclosed in a single photosphere, with a shape resembling a peanut. Other solar mass stars, in nearly circular orbits with periods of a few days or weeks, perpetually turn the same face to each other and form dramatic tidal streams or enormous star spots within a shared and tangled magnetic field (RS Canis Venaticorum variable stars). Among

A type and high mass stars, systems have been found where the tidal attraction between the stars has distorted them into an ellipsoidal shape (ellipsoidal variable stars), sometimes causing a transfer of mass from the larger star to its companion (β Lyrae variables). And stars of any mass may be the Algol type variables, with orbits of months or years – too far apart to interact, but close enough to eclipse each other along our line of sight – that let us measure the diameter of each spectral type of star.

At the other extreme, one of the widest confirmed double stars (the A type system of Fomalhaut and TW Piscis Austrini) is separated by more than 50,000 AU with an age of more than 400 million years. Multiple systems may have the heft to bind even wider orbits: Mizar and Alcor, separated by 74,000 AU, have recently been shown to be bound. The outer limit of orbits that can endure for the life of the component stars is still believed to be around 1,000 to 5,000 AU, but orbits 10 times larger are now confirmed that have survived more than one revolution around the Galaxy.

The typical binary orbit is between these extremes. Among the local, solar type double stars, the median orbital radius is about 50 AU with a median period of 250 years and a wide range of eccentricities distributed around an average of $e = 0.5$ (the semi-major axis (a) is about 15% longer than the semi-minor axis (b); see Appendix B). But Kepler's third law means the system mass will determine the orbital radius for the same 250 year orbital period: a high mass B5V binary must orbit at a radius of around 120 AU, while a low mass M5V type binary can orbit at only 30 AU, the distance of Neptune from the Sun.

Detecting double stars

By definition, a *visual double star* can be resolved into separate components with measurable relative positions. For more than two centuries, these measurements have been made with a filar micrometer: a device that lets the observer adjust the spacing between two parallel filaments in the eyepiece field of view to measure the separation between two stars, then rotate the filaments to align with and measure the position angle. Around 1975, the method of *speckle interferometry* used computers to transform atmospheric turbulence into greatly magnified star images. Two decades later, *long baseline interferometry* used computers to combine the images from widely separated telescopes to create a single high resolution aperture. Interferometry is considered a "visual" technique because it also provides measures of separation and position angle.

Most double stars in the target list were discovered by painstaking visual inspection of every star brighter than an arbitrary magnitude limit. But many were detected by other methods, and it is customary to categorize these systems by the technique used to discover and measure them.

Several hundred double stars have been discovered by analyzing the variable light from an apparently single star – those eclipsing variable stars, mentioned above. Since 1900, more than two thousand have been identified as *spectroscopic binaries*, because the two stars orbit at such high velocities that their mutual spectrum reveals Doppler shifts in the absorption lines of the much brighter star (a single line binary, denoted SB1) or of both similarly bright stars (a double line binary, SB2). Even when no Doppler shifts are apparent, *spectrum binaries* can be detected because the superimposed absorption lines of the two stars are recognizably different, and *photometric binaries* can be identified because the primary star is much brighter than its spectral type predicts. *X-ray binaries* – a white dwarf or neutron star receiving mass from a dying companion – have been identified with X-ray telescopes. Some binaries have even been discovered through a telltale stepwise (rather than instantaneous) extinction of the star's light during *occultation* by the Moon.

A small number are *astrometric binaries*, detected even though the companion is too faint or too close to the glare of the primary star to be imaged. Instead, the small elliptical motion of the primary star can be observed as a sideways wobble in the path and periodic change in the pace of its proper motion across the sky. The companion to Sirius (Figure 1) was identified in this way in 1844, nearly two decades before it was visually detected in 1862.

Finally, several thousand have been identified as *common proper motion (CPM) binaries* because they share the same speed and direction of motion across the sky. (Radial velocity toward or away from the Earth is more difficult to measure, but can be used to calculate the *true motion* in three dimensions.) These are identified by proper motion surveys that rapidly compare or "blink" matched sky photographs taken decades apart or by statistical analysis of the trajectories of stars measured by ground based telescopes and astrometric satellites. Research in the past few decades has found dozens of CPM binaries with an angular separation many times wider than the full Moon. In order to qualify as a double star, the separation of a CPM binary must be small enough to provide an enduring gravitational bond between the stars, but we've seen this limit is at least 50,000 AU in fact, and can be over 1 parsec in theory.

Stars beyond the largest binding distances can still show common proper motion: these *comoving groups*, gravitationally unbound stars with parallel orbits around the Galaxy, have emerged with similar trajectories from the same star forming region. These comoving groups can be huge. Most famous is the Ursa Major association: all but one of the stars in the "Big Dipper" asterism are at the head of an impressive stream of more than 50 stars scattered across 31 constellations.

Even with all the terrestrial and satellite instruments available to us today, visual double stars are local objects, astronomically speaking. Half the systems in the target list are within 120 parsecs of the Sun, and only high mass or high luminosity giant and supergiant systems are bright enough to be included beyond 350 parsecs. Slow positional change or highly inclined orbits prevent us from tracing long period orbits or detecting Doppler shifts; large distances can diminish even huge orbits; limited brightness obscures even neighboring low mass stars. Outside the solar neighborhood, we observe only an incomplete and biased sample of double stars and their components – low mass stars, in particular, are very difficult to detect without infrared telescopes.

As the astronomer Robert Grant Aitken complained over a century ago, a great number of optical pairs have made their way into double star catalogs. (These are retained, though recognized as optical, to prevent "rediscovery.") A repertory of statistical tests has been developed to identify physical systems by appearance alone, and these converge on the visual profile *bright, tight, equal, similar* – the two stars should be little separated, equally bright, and have similar spectral types. The probability that an optical pair will match this profile is very small, but unfortunately this profile excludes the many unequal mass, "giant type" and visually wide CPM doubles we know exist. The real solution calls for data, and this means repeated measures of relative position made over decades or centuries of observation.

Double star catalogs

Double star observations have been painstakingly acquired and cataloged for more than two centuries by a brigade of double star astronomers, and their catalogs form a unique and irreplaceable historical record of celestial change. The target list is compiled from more than 80 of these double star catalogs dating from 1782 to the present (see Appendix D). All these catalogs (and 700 others) are now combined as the *Washington Double Star Catalog* (WDS), the authoritative and frequently updated database of visual double stars maintained since 1964 at the US Naval Observatory (USNO) in Washington, DC.

The attributes essential to include in any double star catalog (besides its celestial coordinates or location in the sky) are: (1) its catalog ID, (2) the component letter codes, (3) the position angle, (4) the separation, (5) the magnitudes of the components and (6) the epoch.

The WDS ID is currently a nine digit abbreviation of the target system's celestial coordinates, with plans to expand to 13 digits. The shorter and more easily recognized Catalog ID, used in the *Atlas* charts and in many references, may not indicate the astronomer who discovered the pair: over 400 double stars credited to F. Wilhelm von Struve (Σ) were actually discovered by William Herschel (H).

The apparent orbit is measured with just two parameters (Figure 4). *Position angle* (θ) is the "clock face" orientation of a line joining the primary (usually brighter) star to the secondary (fainter) star, measured in degrees from the line to celestial north (0°), and increasing counterclockwise through east (90°), south

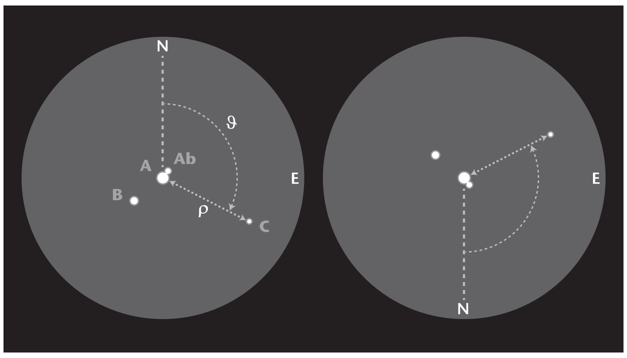

Figure 4 – Double star measurement
A binary star is described by the position angle (θ), and the separation (ρ). The orientation of the field depends on the equipment: (right) an "inverting" astronomical telescope rotates the field by 180° and position angle increases in the counterclockwise direction; (left) a mirror diagonal reverses the field left to right and position angle increases clockwise.

(180°) and west (270°). Because stars appear to drift east to west in a fixed field of view, west is traditionally referred to as *preceding* (abbreviated p.) and east as *following* (f.). These abbreviations, used in combination with *north* (n.) and *south* (s.) in the target list remarks, can point to other objects in a field of view while signaling that the direction is only approximate.

Separation (ρ) is the angular distance between the two stars, measured in arcseconds (″) or, in the target list, in arcminutes (′) if larger than 120″. How wide is a typical double star? The average separation of pairs in the target list is 26″. In comparison, the disk of Jupiter is never smaller than 29″.

Individual stars within multiple stars are identified by a letter *component code*, and measures of position are denoted by the component code combination. The primary star is labeled A, its companion or secondary star is labeled B, and measures of θ and ρ are listed for the pair AB; the third component is labeled C, its position relative to the primary as AC and so on. Frequently a component thought to be a single star turns out to be a close binary, so the component symbol is split by appending lowercase letters and separating the pair with a comma (C becomes the binary Ca,Cb). If one of these is also found to be a binary, the code is split by appending numbers (Ca becomes Ca1,Ca2). New components are assigned the next available letter – D, E, F and so on. Figure 2 illustrates how this sequence of code revisions often signals the hierarchical structure of a multiple star.

In addition to positional measurements, the primary and secondary magnitudes (denoted *m*1 and *m*2) are important to calculate the system magnitude difference or *delta-m* (Δm). As the brightness contrast between the two stars, Δm can be used to estimate the mass ratio (q) of the stars when both are on the main sequence (see Appendix B).

All double stars are continually moving, in orbit around each other and in proper motion across the sky. This makes *epoch*, the year the system was measured, useful to decide if the parameters describe the current appearance of the system. In addition, the meaning of θ changes over time, because precession of the equinoxes changes the celestial direction of true north: epoch allows this to be corrected in historical measures. Although routinely omitted from most double star references, the proper motion of each component is invaluable to suggest whether two stars are moving independently or as a gravitationally bound pair. Finally, the *spectral type* and *luminosity type* are useful to understand the hierarchical structure and age of the system, estimate the system mass, and derive the absolute magnitude necessary to calculate the distance of the system from its apparent magnitude (the so-called *spectroscopic parallax*, see Appendix B).

Telescope optics

With this background understanding of physical double stars, it's time to explore the observing techniques of double star astronomy and the best use of your telescope.

The four basic optical attributes of a telescope are the *aperture* (D), the *objective focal length* (f_o), the objective focal ratio or *relative aperture* (N) of the primary mirror or objective lens and, for visual astronomy, the *eyepiece focal length* (f_e). These define the quantities of magnitude limit, resolution limit, magnification and exit pupil that determine the quality of your telescopic image. Appendix B lists the formulas used to calculate each of these quantities.

The *magnitude limit* (m_L) is an estimate of the faintest star you can detect with your telescope using