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Bright stars and the history of stellar astronomy

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Abstract

"It is a poor workman who blames his tools" – but that said, a stellar astronomer can only work with the material and the tools that have been provided. When it comes to the early history of stellar astronomy the "tool" was the naked eye and the "material" was the collection of so called 'fixed' stars that were visible, these being scattered over that part of the celestial sphere that rose above the horizon. Complaining that there were too few stars or too many was nugatory, as was complaining that these stars had the wrong magnitude distribution, or were too far away, or were not moving fast enough, or were too white. This paper investigates how the history of astronomy, and specifically the pace of astronomical development, was governed by the "material" that the early astronomers were provided with.

Keywords: *visible bright stars*

1 INTRODUCTION

Astronomers are extremely lucky. The reason their science developed first, millennia before say physics, chemistry, and biology, was because the data that they were presented with was extremely limited. Initially they only had four 'species' to look at and to wonder about. In the daytime, their realm, the sky, contained a single large circular yellow disc, which they called the Sun. At night they were confronted with the cold silvery glory of the Moon and a background panoply of the stars. Five of the 'stars' wandered about. All in all, only eight things moved. The Sun, the Moon, Mercury, Venus, Mars, Jupiter, and Saturn moved around the sky in a rather restricted way, sticking at all times to the zodiacal band, and for the most part moving in the same direction. And the sky itself moved, spinning uniformly about an axis through the Pole Star (as seen by northern hemisphere observers). This produced the regular sequence of easterly rising, southerly transiting, and westerly setting.

Also, from a scientific standpoint, the 'fixed' stars were well behaved. Unlike, say, a flock of birds—each bird of similar appearance—the visible fixed stars had different brightnesses. But the range was tractable; the shiniest visible star was only a few hundred times brighter than the faintest that could be seen. Also, rather like baby bear's porridge, the number was 'just right'. The ancient night-time sky-watcher was not confronted with a mere handful of stars, or with a confusing multitude. There are, for example, only about 450 stars brighter than visual apparent magnitude four, and only about half of these are above the horizon at any one time. Many (e.g. see Ferguson 1803:349) commented on the fact that even though an observer's first impression was that the stars in the sky "... seem to be without number ...", they are actually "... much thinner sown than he was aware of ...", and that we should ponder "... how seldom the Moon meets with any star in her way."

The task of recording the movement of the Moon and the planets was helped greatly by the 'celestial graph paper' that the background stars provided. Here again astronomers were extremely lucky because this celestial graph paper was easy to memorize. Far from its being a boring grid of equally-spaced uniform points, the stellar background formed a hugely varied pattern of bright and less bright stars. These could be easily collected into memorable groups, the differing shapes of these groups leading to the sky being dragooned into a host of constellations representing animals, birds, fish, gods, dragons, rivers, and the like. Again, luckily, the shapes of the constellations and their relative positioning did not change detectably from generation to generation.

In this paper we are going to consider some of the important characteristics of the visible stellar background, and we are going to briefly allude to their historical significance.

2 STELLAR NUMBER VERSUS BRIGHTNESS

Lang (1991:168) provides a useful list of the four hundred and forty-six stars in the whole sky that are brighter than magnitude 4. The 'magnitude' system was introduced by Hipparchus in around 134 BC. Supposedly encouraged by the appearance of a nova in the constellation of Scorpio, he decided to produce a new catalogue of stars, working from his observatory in Rhodes (latitude 36° N). Not only did he list the positional coordinates of each of 1,028 stars (1,025 plus three duplicates), grouped into forty-eight constellations (twelve zodiacal, twenty-one in the northern sky and fifteen in the southern sky), he also introduced a grading system representing the relative 'importance' of the star. This started at 1 for the brightest fifteen stars and increased to 6, the latter grade containing all those stars that were barely visible to the naked eye. (According to Arago (1854), Hipparchus recorded fifteen stars of first magnitude, forty-five of second magnitude, two hundred and eight of third magnitude, four hundred and seventy-four of fourth magnitude, two hundred and seventeen of fifth magnitude, forty-nine of sixth magnitude, nine obscure, and five nebulous stars.) The extant version of this catalogue is reproduced in Ptolemy's *Syntaxis,* published around AD 150. Considering the stars that Hipparchus could see from his Rhodes vantage point, his 'importance' magnitude 1 star group contains stars which have modern measured visual magnitudes less than about +1.5. From Rhodes, Hipparchus would have seen no stars with southern declinations greater than 54° South, and, due to atmospheric absorption, would have had difficulty seeing stars below about 50° South. This rules out about 12% of the celestial sphere, including the very bright stars Achernar (α Eri, apparent magnitude 0.46, declination 57° S), Rigel (or Rigil) Kentaurus (α Cen, apparent magnitude –0.01, declination 60° S) and possibly Canopus (α Car, apparent magnitude –0.72, declination 52° S).

During the astronomical renaissance, up to about the year AD 1600, all celestial maps were based on the Ptolemaic (Hipparchus) star catalogue. On these maps, stars of magnitudes 1 through 6 were represented by circular glyphs of ever-decreasing sizes, a symbolization that is still in use today.

No one seemed to question the number of stars included. Why did Hipparchus catalogue 1,025 stars, as opposed to say 500 or 2,000? Using equation (3) below we note that from Rhodes Hipparchus could have seen about 1025 stars brighter than visual magnitude 4.8, with 500 brighter than magnitude 4.2 and 2,000 brighter than magnitude 5.4. Maybe the astronomers of the day were fatalistic. Following *Genesis* 1:16 where God "... made the stars also ...", they may have concluded that he made just enough for their purpose, no more and no less.

The dawn of astrophysical photometry saw greater significance placed on stellar brightnesses. William Herschel concluded that the actual brightnesses of stars with magnitudes 1, 2, 3, 4, 5 and 6 were as 100, 25, 12, 6, 2, and 1 (see Chambers, 1867: 493). When Sir John Herschel was at the Cape in the mid 1830s he noted that the average star of 1st magnitude was about a hundred times brighter than one of 6th magnitude (see Herschel, 1871).

The magnitude-brightness relationship was first placed on a firm footing by the Oxford astronomer N R Pogson (1857), who suggested that an absolute scale of magnitudes be introduced such that a star of magnitude m was *exactly* $10^{2/5}$ brighter than one of magnitude $(m+1)$. Pogson tacitly assumed that the human eye responds uniformly to the logarithm of the stellar brightness (logarithms being much in vogue during the eighteenth and nineteenth centuries).

This response characteristic was formalised in 1860 by G T Fechner, and can be expressed as sensation ∝ log (stimulus). Under these circumstances the measured brightnesses of stars, b, with given 'Hipparchus' magnitudes, m, are forced to fit a relationship of the form

$$\log b = c_1 + c_2 m, \qquad (1)$$

where c_1 and c_2 are constants. If it is assumed that a star of 1st magnitude is exactly a hundred times brighter than one of 6th magnitude then $c_2 = -0.4$. The assumed logarithmic physiological response of the eye's retina to visual stimuli led to the stellar visual magnitude scale 6th, 5th, 4th, 3rd, 2nd and 1st being equivalent to stellar brightnesses of 1, 2.51, 6.3, 16, 40, and 100 respectively.

Unfortunately, even at the time, some researchers doubted the veracity of the logarithmic relationship. It is now realized (e.g. see Stevens, 1961) that the eye's perception of stellar brightness is better described by a power law such that sensation ∝ $(\text{stimulus})^n$. Here

$$\log m = c_3 + n \log b. \qquad (2)$$

Young (1984) compared the stellar magnitudes in Ptolemy's *Almagest* with modern accurate photometric brightnesses and concluded that $n = -(0.4 \pm 0.1)$, a value close to $n = -0.5$ which was suggested by John Herschel in 1847. The universal acceptance of equation (1) in present-day astronomical circles is rather surprising considering the doubts expressed by, for example, John Herschel (1871:563-564).

There is another important question concerning the work of Hipparchus. Sirius (apparent magnitude –1.46) was about 960 times brighter than the faintest visible 6th magnitude star that could be detected. Why was this range of brightnesses divided into six intervals as opposed to say four or ten? We are not told. Interestingly, in the early fifteenth century Ulugh Beg (1394–1449) subdivided each of the Hipparchian six categories into three subdivisions, with a distinction being made between small, intermediate and large stars of each specific magnitude (see Humboldt, 1851:121). Decimal gradations were introduced in the early nineteenth century by F G W Struve and F W A Argelander.

Following the accepted logarithmic tradition expressed by equation (1), Richard Proctor (1892:717) introduced the number 1.585 (this being $10^{2/10}$), which he referred to as the 'distance-ratio'. This corresponded to the proportional distance to which a star must be removed in order that its magnitude would be increased by unity. Imagine a series of spherical shells with radii r, $1.585r$, 1.585^2r, 1.585^3r, etc., centred on the observer. These shells enclose volumes that increase successively by a factor of 3.981 (this being $10^{6/10}$). So (i) *if* stars were distributed uniformly throughout space, and (ii) *if* stars all had exactly the same luminosity, and (iii) *if* space was completely transparent (i.e. there was no interstellar absorption) we would therefore expect the number, N_{m+1}, of stars brighter than magnitude $(m+1)$ to be exactly 3.981 times greater than the number N_m, of stars brighter than magnitude m. Is it? Figure 1 shows the way in which the number of bright stars with magnitudes between m and $m + 0.25$ vary with magnitude over the range $-1.4 < m < 4.0$. Figure 2 is a plot of the logarithm of the cumulative number N_m, as a function of m, over the same range. The linear fit to the data in Figure 2 has the form

$$\log N_m = (0.654 \pm 0.04) + (0.5003 \pm 0.0013)\, m. \qquad (3)$$

Notice that $10^{0.5003}$ is equal to 3.164 and not 3.981, so one (at least) of the three assumptions listed above is erroneous. Notice, however, that the three assumptions do present a reasonable explanation for the number-brightness relation of the stars that are seen in the sky. If one asks "Why do stars have different brightnesses?" the fact that they might all have similar luminosities but be at different distances from the observer is a reasonable explanation. If one asks "Why are there many more faint stars than bright ones?", then the way in which the volume of a uniformly-dense visible cosmos increases with its radius offers a reasonable clue to the explanation.

Before we consider who, in the history of astronomy, worried about questions such as these, let us briefly discuss limiting stellar magnitudes. In the period before 1609, before Galileo introduced the astronomical telescope to our subject, astronomers were confined to the use of the naked eye, with its limited dark-adapted pupil diameter. On a clear dark moonless night the typical dark-adapted eye can detect stars brighter than about 6th magnitude. The objective lens or mirror of a telescope enables more light to be collected and concentrated into the eye pupil. The limiting magnitude, m_{lim}, of the stars that can then be detected increases as a function of the clear aperture A

(mm) of the instrument being used. According to, for example, Ridpath (2004:29)

$$m_{\lim} = 2.68 + 5.0 \log A. \qquad (4)$$

Robert Hooke, in his famous work *Micrographia* (1665:241), was the first to consider the relationship between telescope aperture and the number of stars that could be detected. Cassini (1717:260) also touched on the same problem. But unfortunately he suggesting that the ability of a telescope to detect faint stars was a function of its magnification. William Herschel commented on the magnitude-distance relationship, echoing the views expressed by Isaac Newton around 1692 (see, for example, Hoskin 1977). Herschel (1782:102) wrote, "Let the differences in their apparent magnitudes be owing to their different distances, so that a star of the second, third or fourth magnitude is two, three or four times as far off as one of the first." Halley (1720) perceptively took the Newtonian suggestion to its correct conclusion. Thinking in terms of stars all being similar in luminosity and size to the Sun, and being distributed at more or less regular intervals throughout space, the first magnitude stars were clearly those closest to the Sun. Halley assumed that there were thirteen first magnitude stars. He wrote that

> … at twice the distance from the Sun there may be placed four times as many, or 52; which, with the same allowance, would nearly represent the number of the Stars we find to be of the 2d magnitude: so 9 × 13 or 117, for those at three times the distance: and at ten times the distance 100 × 13 or 1300 Stars; which distance may perhaps diminish the light of any of the Stars of the first magnitude to that of the sixth, it being but the hundredth part of what, at the present, they appear with. (ibid.).

This is exactly the definition that Pogson used 130 years later when introducing the present-day logarithmic magnitude scale.

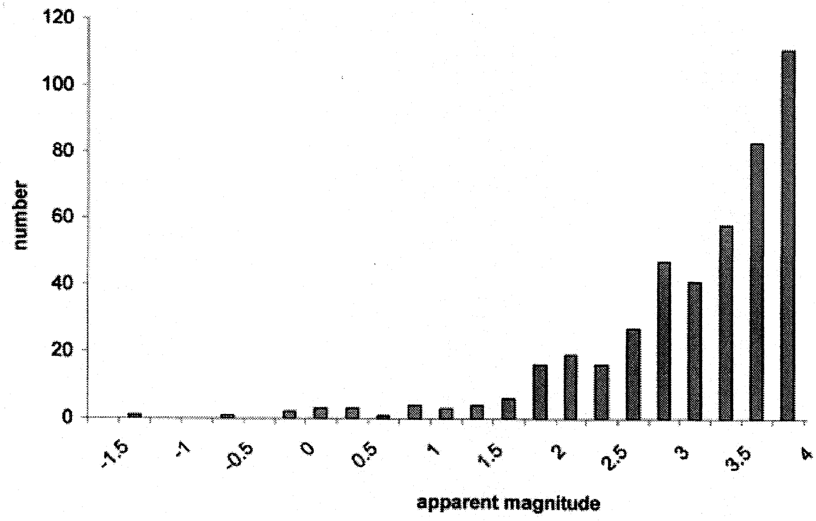

Figure 1. The histogram shows the way in which the number of 'fixed' bright stars with magnitudes between m and m+0.25 vary as a function of magnitude. These data have been taken from Lang (1991).

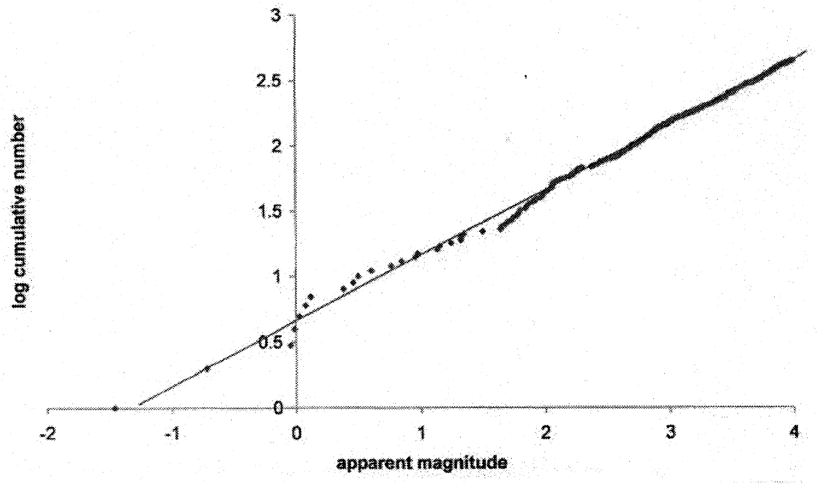

Figure 2. A plot of the logarithm of the cumulative number of stars brighter than a visual magnitude m, as a function of m. The line through the data is represented by equation (3).

Galileo's first telescope, in 1609, had a usable aperture of 1.5 cm. The telescope used by Huygens in 1655 had an aperture of 5.7 cm, the Dollond 1757 achromat, 10 cm, and the 1820 great Dorpat refractor, 24 cm. These increases in aperture lead to an increase in stellar limiting magnitude and a huge change in the number of stars that could be detected. The size of this increase was a matter of considerable debate. What was the teleological significance of this profusion of faint stars? Why had God bothered to make stars that could not be seen with the naked eye? Perhaps it was to encourage us to build ever-larger telescopes! As larger and larger lenses were used, more and more increasingly fainter stars were seen. Where would it end? Would one arrive at a telescope size that would enable the astronomer to detect all the stars in the Universe? Would larger telescopes then become nugatory? Did anyone ask "Just how many stars are there in the Universe?" (When my students ask this question I simply say "10^{23}", quickly multiplying my guess as to how many galaxies there are (10^{11}) by 10^{12}, the estimated number of stars in each galaxy.)

In the early seventeenth century, Galileo noted that "... the Galaxy is nothing else than a congeries of innumerable stars distributed in clusters. To whatever region of it you direct your spyglass, an immense number of stars immediately offer themselves to view, of which many appear rather large and very conspicuous but the multitude of small ones is truly unfathomable." (cited in van Helden, 1989:62). Around this time in the history of astronomy we quickly saw the rather cosy confined Aristotelian cosmos, with its small number of nested spheres, being replaced by a cosmos of infinite and homogeneous extent governed by Euclidean geometry. It was suggested that the newly-observed telescopic stars were not seen by the unassisted eye simply because they are too far away. Telescopes did not change the 'look' of the stars. They were still points of light. Ferguson (1803:2) suggested that this "... proves them to be at least 400 thousand times farther from us than we are from the Sun." Thereafter, many popular books were rather loose in their terminology. Aspin (1825: 26), for example, writes: "... the fixed stars, according to their size and brilliancy, are divided into magnitudes." Size surely did not come into it. With the exception of the Sun, all stars appeared as point sources.

Let us return briefly to equation (3) and the magnitude distribution index, that is the number 3.164. William Herschel (1784) tried to estimate the extent of our Galaxy by 'star gauging'. To this end he simply pointed his telescope in six hundred and eighty-three different directions and counted the number of stars that he could see in each field of view. Here he was simply counting down to a specific limiting stellar magnitude and the number of stars seen was taken to be proportional to the cube of the distance to the edge of the system. The results were used to arrive at a rough shape of the universe, which in those days was regarded as being a single galaxy with the Solar System in a central position. A more sophisticated approach was to count stars down to different magnitude limits. This, however, needed an accurate estimation of the magnitudes of all the stars in the field of view. Many years had to elapse before this was possible (e.g. see Seares, 1928).

In 1856, Lardner wrote "The number of stars in each succeeding magnitude increases rapidly as their splendour diminishes. Thus there are no more than 18 or 20 of the first magnitude, there are 50 or 60 of the second, and about 200 of the third, and so on; the total number visible to the naked eye, up to the sixth magnitude inclusive, being from 5000 to 6000." (Lardner, 1856:150). Later he wrote that stars usually "... derive their variety of lustre almost entirely from their places in the universe being at various distances from us." (Lardner, 1875:377). Some years earlier, Humboldt (1851:141) reviewed the work of many star-counters and concluded that "... it is well known that on considering the whole mass, we find each class contains about three times as many stars as the one preceding." He went on to quote a population of twenty for 1st magnitude; sixty-five for 2nd magnitude; one hundred and ninety for 3rd magnitude; four hundred and twenty-five for 4th magnitude; 1,100 for 5th magnitude; 3,200 for 6th magnitude; 13,000 for 7th magnitude; 40,000 for 8th magnitude, and 142,000 for 9th magnitude.

3 STAR NUMBERS VERSUS DISTANCE

Our perception of the cosmos changed drastically with the general acceptance of the heliocentric model put forward by Copernicus (1473–1543) in *De Revolutionibis Orbium Coelestrium.* Copernicus insisted that the visible world of the fixed stars was immeasurably large (see Koyré, 1957:32). Not only, as asserted by Ptolemy, was the Earth, in comparison to the skies, "as a point", but, to Copernicus, Earth's annual orbit around the Sun was so small as to be similarly point-like. More importantly, the Copernican system presented astronomers with a possible mechanism for distance measuring. In its six-monthly journey from one side of the Solar System to the other, Earth moves two astronomical units (2 AU), a distance we now know to be around 3×10^8 km. This movement makes nearby stars move with respect to more distant stars, and a measurement of this parallactic movement would enable stellar distances to be calculated. However, astronomers had to wait until 1838 before their instruments were sufficiently sophisticated to enable this parallactic angle to be measurable.

How far away are the stars that can be seen in the sky with the naked eye? The fact that they appear as point sources indicates that their discs subtend at Earth an angle less than the 1 minute of arc resolution of the naked eye. If they had the same physical dimension as the Sun this fact alone put them further away than 30 au. Michell (1767) noted that if the stars had the same luminosity as the Sun, the fact that the brightest star was about as bright as the planet Saturn indicated that it was around 220,000 times further away than the Sun, and had a parallax of less than 2 seconds of arc.

Let us, however, return to the list of the four hundred and forty-six stars in the whole sky that are brighter than 4th magnitude (Lang, 1991:168). Figure 3 shows how the number of these stars varies as a function of their distance. The median distance is about 39 pc. The closest star in the group is α Cen (at 1.3 pc) and the four most distant are π^4 Ori, α Col, ε Cma, and δ Seg at around 100 pc. We would expect the median distance, d_{med} (pc) to vary as a function of the apparent magnitude of the stars being observed. The $m < 4$ data have been sorted according to apparent magnitude and divided into seven equally-populated star groups (see Figure 4). The relationship is rather crude, and it is roughly represented by

$$d_{\mathrm{med}} = (29.7 \pm 6.9) + (2.6 \pm 2.1)\ m. \qquad (5)$$

This relationship lends some credence to the suggestion that the brightest stars are the closest.

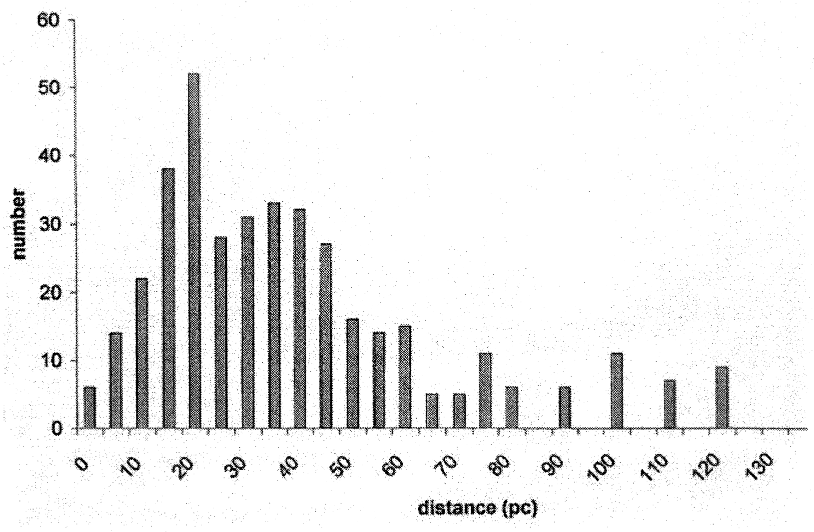

Figure 3. The histogram shows the way in which the number of bright, $m < 4$, stars vary as a function of their distance, the data being divided into 5 pc bins. Fifty percent of the stars are closer than 39 pc.

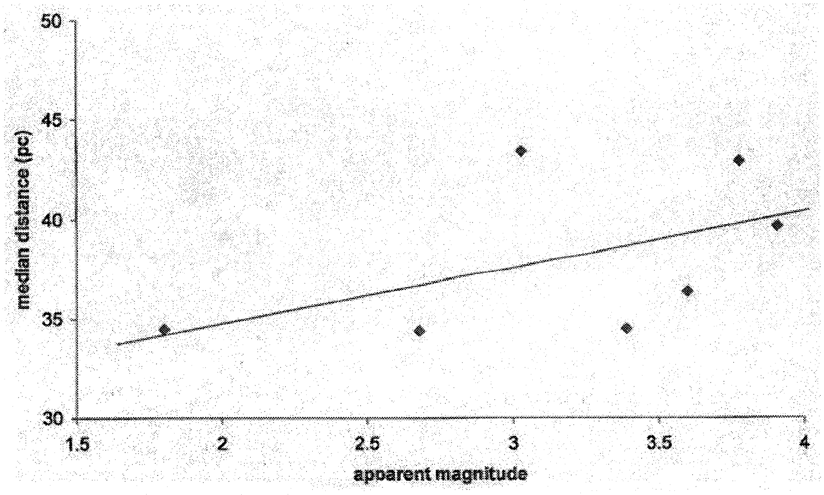

Figure 4. The median distance of the visible stars is plotted as a function of magnitude. As is to be expected, the brighter stars are somewhat closer than the fainter ones but the relationship is rather weak over the magnitude range of naked-eye stars.

A star at the median distance of 39 pc has a six-monthly parallactic shift of 0.05 arc seconds. The smallness of this angle underlines the great accuracy required for stellar distance measurement. October 1838 saw the first announcement of a measured parallax. This was for the 5.2 magnitude star 61 Cygni, a 'flying star' with a huge proper motion of 5,260 arc seconds per millennium. Friedrich Bessel had been observing this star using the Königsberg Observatory's 6.25-inch Fraunhofer heliometer. At very nearly the same time, Thomas Henderson, working in South Africa, reported the parallax of α Centauri, another 'flying star'. Other parallaxes were reported in steady succession over the next fifty years, and by 1887 the parallaxes of twenty-eight stars had been published, eleven of these stars having $m < 4.0$. Note that beyond 20 pc parallaxes measured using photographic plates taken on long-focus telescopes become too inaccurate; distances to more distant stars are usually obtained using the spectroscopic parallax technique.

4 NUMBER VERSES LUMINOSITY

In the previous Section we mentioned the common assumption that all naked-eye visible stars might be thought of as having the same luminosity. As the distances to more and more of these stars became known this assumption could be checked. The four hundred and forty-six stars brighter than 4th apparent magnitude can be sorted according to their absolute magnitude, and this is shown in Figure 5. The median absolute magnitude is found to be +0.29, making the median star about sixty-six times more luminous than the Sun (which has an absolute visual magnitude of +4.83). The histogram in Figure 5 is a reasonably approximation to a Gaussian curve, and indicates that about 23% of the $m < 4.0$ bright, visible stars have absolute magnitudes in the 0.29 ± 0.5 range. Increasing the range to 0.29 ± 1.0, 0.29 ± 1.5, and 0.29 ± 2.0 encompasses 44, 61, and 77% of the stars. The 'similar luminosity' assumption for the stars that can be seen with the naked eye is not too unreasonable. William Herschel and Richard Proctor were not, however, to know that the absolute magnitude histogram was a reasonably-narrow quasi-Gaussian. This could not be confirmed until the distances of all the $m < 4^{th}$ magnitude stars had been obtained, in the early twentieth century.

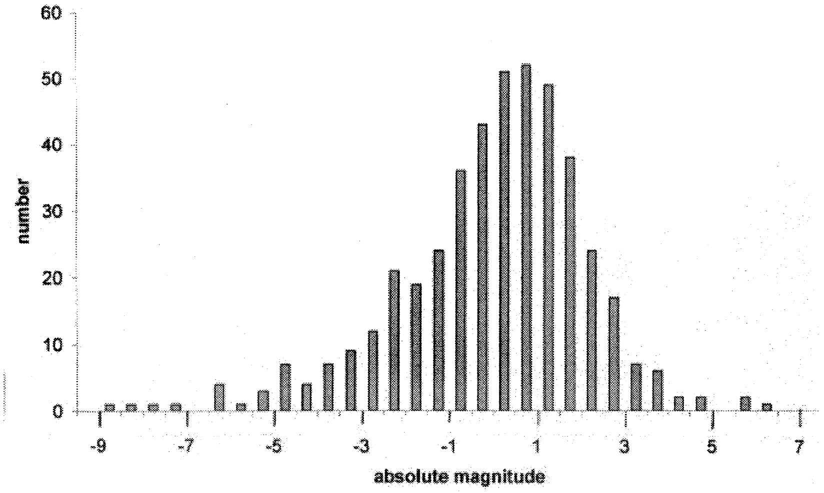

Figure 5. The histogram shows the distribution of the absolute magnitudes of the $m < 4$ naked eye stars, the stars being sorted into bins that are 0.5 magnitudes wide. The median absolute magnitude is about +0.29.

5 NUMBER VERSUS COLOUR

A crude estimation of a star's colour can be derived from the colour index. This is defined as being the difference between the apparent magnitudes of the star when observed through a blue filter, B, (centred on a wavelength of 4,400 Å with an effective bandwidth of 980 Å) and through a visual filter, V, (centred on 5,500 Å with an effective bandwidth of 890 Å).

There has been much debate about the ability of the naked eye to estimate the colour of a bright star with any degree of accuracy (e.g. see Cohen & Oliver, 1981; and Murdin, 1981). Murdin (1981) compared colour observations recorded by William Herschel, Admiral W H Smyth and F G W Struve and concluded that the colours were real but also somewhat subjective. He also found that the correlation between the results given by Minnaert (1940:300) and the modern colour index scale was excellent. This analysis is expanded on in Table 1.

It is quite clear that not all stars appear white, but it is also obvious that star colours are subtle. In Ptolemy's star catalogue, the *Almagest*, only six stars were marked as having distinctive colouration. These were α Boö (Arcturus, B–V = 1.24), α Tau (Aldebaran, B–V = 1.53), β Gem (Pollux, B–V = 1.00), α Sco (Antares, B–V = 1.83), α Ori (Betelgeuse, B–V = 1.86) and, somewhat surprisingly (see Malin & Murdin, 1984:88) α CMa (Sirius, B–V = –0.01). Ptolemy referred to all the stars as being 'hypokirros', a word that translates as 'somewhat yellow'. This term is considerably more conservative than the rather florid adjectives employed by Allen (1899), who had Arcturus as golden yellow, Aldebaran as pale rose, Pollux as orange, Antares as fiery red, Betelgeuse as orange, and Sirius as brilliant white.

Why Ptolemy only singled out six out of the 1,025 recorded stars is somewhat surprising. Cohen and Oliver (1981) note that only the cool stars of spectral classes K and M really show any colour other than white or blue-white. Two factors explain the small number of stars that are perceived to be coloured. First, only about 30% of the stars in Lang's (1991:168) list fall into the K and M classes, and secondly, the dark-adapted eye only records the brighter of the cool visible stars as being coloured. The typical first magnitude naked-eye star is in spectral class A, with a colour temperature of 10,000 K. Averaging over the fainter naked-eye stars gives a colour temperature of around 8,000 K, equivalent to a mid-F spectral class.

Two other things affect the perceived colour of a star. Star light is reddened due to scattering in Earth's atmosphere, and this reddening increases as the stars near the horizon. The fact that Sirius (declination –16°.6) and Antares (declination –26°) stay relatively close to the horizon for an observer in Rhodes might explain their perceived colour. The interstellar medium also reddens starlight, so the more distant stars of a specific spectral class are generally redder than the closer ones.

6 NUMBER VERSUS PROPER MOTION

Edmond Halley (1656–1742) discovered proper motion—that stars are actually moving and changing their relative positions, and therefore the shape of the constellations. After Halley the 'fixed' stars were fixed no more. As with many astronomical discoveries, Halley (1717) was actually looking for something else.

He was preparing his *Astronomical Tables* and re-determining the rate of precession of the equinoxes, mindful of the fact that the obliquity of the ecliptic was slowly decreasing. To this end he was comparing the declination of stars given in current catalogues with the declinations measured by Timocharis and Aristyllus in about 300 BC and Hipparchus around 130 BC and recorded by Ptolemy in the third chapter of the seventh book of the *Almagest*. The obliquity had changed by about 20 arc minutes since the time of Hipparchus. Three stars had not, however, followed the expected change in ecliptic latitude and longitude, these being Aldebaran (α Tauri, which was called Palilicium, or the Bulls Eye, by Halley), Sirius (α Canis Majoris) and Arcturus (α Boötes). To quote Halley (1717:737):

> ... all these three Stars are found to be above a degree more Southerly at this time than the Antients reckoned them ... What shall we say then? It is scarce credible that the Antients could be deceived in so plain a matter, three Observers confirming each other. Again these Stars being the most conspicuous in Heaven, are in all probability the nearest to the Earth, and if they have any particular Motion of their own, it is most likely to be perceived in them, which in so long a time as 1800 Years may shew it self by the alteration of their places, though it be utterly imperceptible in the space of a single Century of Years.

Table 1: An astronomical colour scale for bright naked eye stars based on the work of Minnaert (1940) and Murdin (1981)

Colour	Examples	Colour index range	Stellar temperature range (K)*	Number[#] %
White	α CMa (Sirius) α Lyr (Vega) α Vir (Spica) α Ori (Rigel)	<0.0	>10,000	21
White-yellow	α Leo (Regulus) β UMa (Merak) α CMi (Procyon) α Aql (Altair)	0.0–0.45	6500–10,000	25
Pale yellow	α UMi (Polaris) Sun [Venus, Jupiter]	0.45–0.75	5300–6500	7
Pure yellow [Saturn]	α Boö (Arcturus) α UMa (Dubhe)	0.75–1.0	4600–5300	13
Deep Yellow	β UMi (Kochab) β Gem (Pollux)	1.0–1.3	3950–4600	18
Orange-yellow	α Tau (Aldebaran)	1.3–1.65	3400–3950	14
Orange	α Sco (Antares) α Ori (Betelgeuse) [Mars]	>1.65	<3400	2

* The stellar temperature (K) has been obtained by using the empirical relationship $(B - V) = -0.865 + (8540/T)$.

[#] The percentages have been obtained by analysing the 446 stars brighter than 4th magnitude given in Lang (1991)

Turning to, for example, Motz & Duveen (1977: 257) and Dibon-Smith (1992:35, 45,193), we find that Aldebaran, Sirius, and Arcturus have listed proper motions of 203, 1,324, and 2,285 arc seconds per millennium respectively. The latter two could certainly have been detected by Halley over the 1,800 years interval, but the proper motion of Aldebaran could not. Interestingly, Ronan (1969:201) lists the three moving stars as Arcturus, Procyon, and Sirius. Procyon (α Canis Minoris), with a proper motion of 1,247 arc seconds per millennium, is a much more likely inclusion as a member of the 'moving three'.

Figure 6 shows a histogram of the proper motions of the 100 brightest stars in the sky. Rigel Kentaurus (α Centauri) has the largest proper motion, this being 3,678 arc seconds per millennium. This very bright star would have been easily recorded by Halley from St Helena, but, with a declination of –60.4°, was much too far south to have been recorded in the *Almagest*. Figure 6 shows that 96% of the bright stars have proper motions <740 arc seconds per millennium, and this motion was too small to be detected by Halley. In Figure 7 we plot proper motion as a function of apparent magnitude for those stars with proper motions >400 arc seconds per millennium and with $m < 6$. It is clear that Halley's ability to discover proper motion was not only limited by stellar declination but also by stellar magnitude. Northern 'fast' stars such as 61 Cyg and μ Cas were too faint to have detectable proper motion, while β Hydri and ζ Tucanae were also too far south.

The fact that a few of the constellation-defining 'fixed' stars actually moved was a completely revolutionary and unexpected concept in the early eighteenth century. It provided an excellent reason for observing stars again and again, hopefully with ever-increasing accuracy. The fact that Halley had great faith in the data recorded in the *Almagest* is also noteworthy. He pioneered the use of ancient data in the quest for modern astronomical knowledge, his work on the variability of the salinity of the Mediterranean and the Earth-Moon distance being other examples.

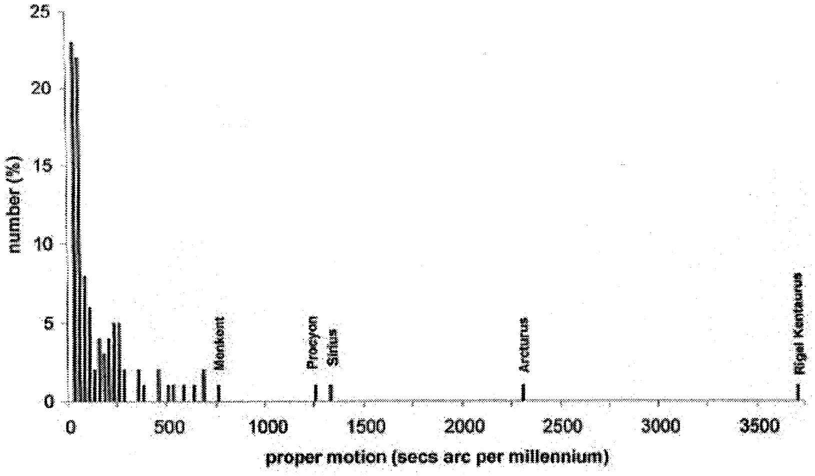

Figure 6 The histogram shows the distribution of the proper motions of the one hundred brightest stars in the sky. Rigel Kentaurus (α Cen, declination –60°.8) was too far south to be recorded by Hipparchus. Menkent (θ Cen, declination –36°.40) wasn't, but the proper motion of 738 arc seconds per millennium was too small for Halley to detect.

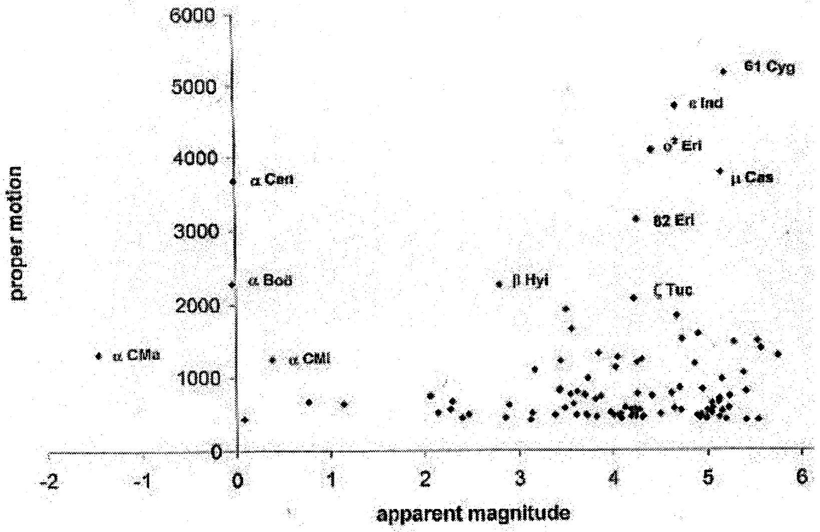

Figure 7. Naked-eye stars with proper motions >400 arc seconds per millennium have been selected from the data given in Dibon-Smith (1992) and the proper motion is plotted as a function of apparent magnitude. Some of the faster stars have been named.

Halley's suggestion of proper motion was soon followed up. In 1738, Jacques Cassini showed that Arcturus had moved by 5 arc minutes in 152 years (see Chambers, 1867:493). By 1783, William Herschel published a list of twenty-seven proper motions (all >200 arc seconds per millennium), and he used these to show that the Sun was moving in the direction of Lambda Herculis:

> That several of the fixed stars have a proper motion is now already so well confirmed, that it will admit of no further doubt. From the time this was first suspected by Dr Halley we have continued observations that shew Arcturus, Sirius, Aldebaran, Procyon, Castor, Rigel, Altair, and many more, to be actually in motion; and considering the shortness of the time we have had observations accurate enough for the purpose, we may rather wonder that we have already been able to find the motions of so many, than that we have not discovered the like alterations in all the rest. (Herschel, 1783:247).

Halley's suggestion that the brightest stars (being probably the closest) have the largest proper motion can be easily put to the test by referring to Figure 7. The relationship is not strong, to say the least. It was not long before accurate meridian-circle work enabled a few much faster and fainter stars to be found. Chambers (1867:493) lists the star 2151 Argus (proper motion 7,870 arc seconds per millennium), ε Indi (4696), 1830 Groombridge (6970, in Ursa Major), and 61 Cygni (5110). At the present time, the record for the largest proper motion is held by Barnard's Star, a 9.56 magnitude star in Ophiuchus that was discovered by the American astronomer, E E Barnard, in 1916. This star is only 1.8 pc away and is moving at 10,270 arc seconds per millennium.

7 RADIAL VELOCITY

In 1842 Christian Doppler (1803-53) noticed that the detected wavelength of a source varied as a function of the relative velocity between the observer and the source. The relationship is $\Delta\lambda/\lambda = v/c$, where λ is the wavelength emitted by the source and $\Delta\lambda$ is the change in wavelength due to the source moving at a velocity v with respect to the observer, c being the well-known velocity of light (299,793 km s^{-1}). The Doppler equation immediately opened up the prospect of being able to measure the line-of-sight velocities of astronomical objects, their wavelengths being red-shifted if they were moving away from the observer and blue-shifted if they were approaching. All one needs is a sensitive well-calibrated spectrometer. Doppler controversially and erroneously maintained that the different colours exhibited by the visible stars were indications of their large line-of-site relative velocities, and this hindered the acceptance of his theory for some time.

Lang (1991:168) lists the parameters of the four hundred and forty-six stars brighter than 4th visual magnitude, and the distribution of their radial velocities is shown in Figure 8. Two things are clear. The histogram is reasonably symmetrical about the zero velocity, showing that about as many bright stars are moving towards us as are moving away. And the maximum velocities are +99 km s^{-1} (δ Lep; declination –21°), +89 km s^{-1} (δ Col; declination –36°), +88 km s^{-1} (σ Pup; declination –43°), –87 km s^{-1} (η Cep; declination +62°), +75 km s^{-1} (α Phe; declination –42°), and –70 km s^{-1} (ζ Her; declination +32°). So the maximum value of $\Delta\lambda/\lambda$ for the visible bright stars is about 3×10^{-4}.

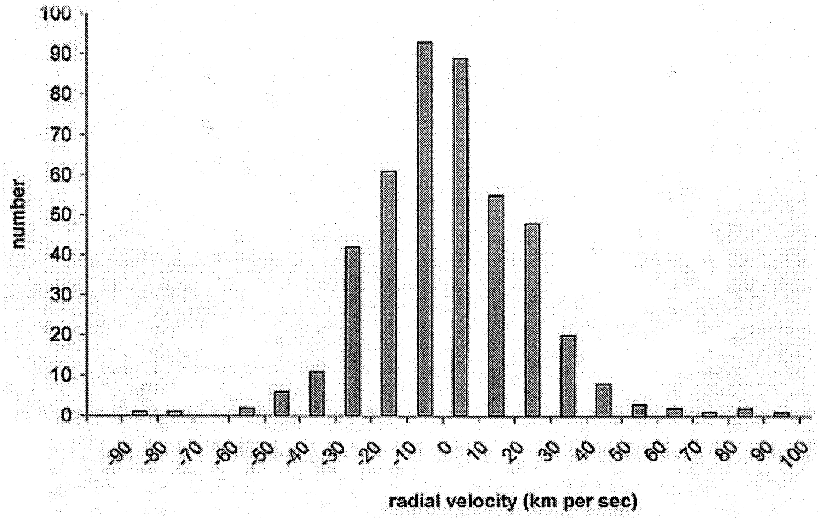

Figure 8. The histogram shows the distribution of radial velocities for the four hundred and forty-six stars with $m < 4$.

The median radial velocity of the $m < 4$th magnitude stars (ignoring sign) is about 13.5 km s^{-1} making the median value of $\Delta\lambda/\lambda$ about 5×10^{-5}. Measuring this small wavelength shift was clearly not going to be easy.

What were the clues available to nineteenth-century astronomers to enable them to pick out the stars with large radial velocities? Figure 9 shows the modulus of the radial velocity plotted as a function of apparent magnitude. There is no obvious relationship. Figure 10 shows the modulus of the radial velocity plotted as a function of proper motion, but again the relationship is obscure. Considering the difficulty of measuring the wavelength shift, most astronomers took the simple expediency of concentrating on the brightest stars, that is those that would give the clearest spectra at the maximum spectral dispersion. To quote Agnes Clerke (1885:426), the method

> ... needs a powerfully dispersive spectroscope to show line-displacements of the minute order in question; and powerful dispersion involves a strictly proportionate enfeeblement of light. This, where the supply is already to a deplorable extent niggardly, can ill be afforded; and it ensues that the operation of determining a star's approach or recession is, even apart from atmospheric obstacles, an excessively delicate one.

William Huggins (1868) was the first astronomer to practically apply the Doppler relationship to the measurement of radial velocities. He used a twin-prism visual spectroscope attached to the 20.3-cm refractor sited at his private observatory at Tulse Hill in south London. He observed Sirius, not only because it was very bright but also because it had four strong Fraunhofer lines in its visual spectrum. Unfortunately visual results were only accurate to about ±25 km s^{-1}. In 1863, Huggins was also one of the first to photograph stellar spectra, using the wet-plate method, but it took some time before this technique was applied to radial velocity measurements. Henry Draper in the USA followed in 1872. In this same year Huggins published radial velocities for Rigel, Betelgeuse, Castor, Regulus, Arcturus, Vega, and Deneb. By 1890, the Royal Observatory at Greenwich had produced a list of thirty-four radial velocities, concentrating on bright constellation stars (see Chambers, 1890:373), but results were affected by serious systematic errors. Photographic observations of radial velocities started to be made in the late 1880s, and accurate values (to about ±3 km s^{-1}) were first obtained by H C Vogel and J Scheiner at Potsdam around 1887 for Sirius, Procyon, Rigel, and Arcturus. Young (1895:536) lists fifty-one radial velocities taken from the work of Vogel, these being for stars brighter than magnitude 2.4.

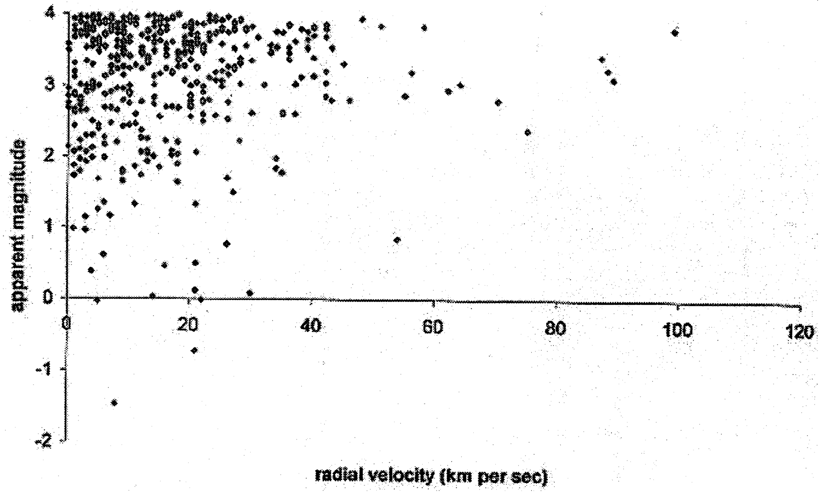

Figure 9. The radial velocity is plotted as a function of apparent magnitude for the four hundred and forty-six stars with $m < 4$. There is no obvious relationship between the two quantities.

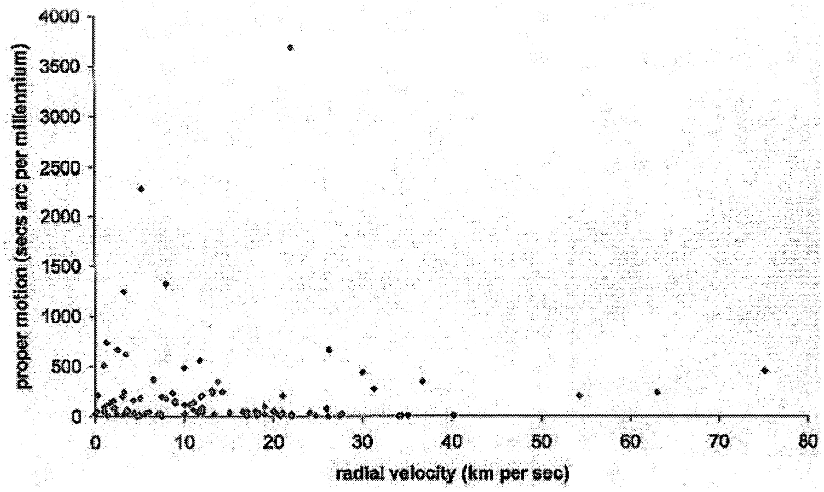

Figure 10. The proper motion of the one hundred brightest stars in the sky is plotted as a function of their radial velocity. If the stellar velocity vectors were inclined randomly to the line of sight one might expect a correlation between these two quantities. On the basis of the bright star data, this relationship is not convincing.

8 CONCLUSIONS

We have analysed the parameters of the bright stars that can be seen in the sky and we have discussed the relevance of these parameters to the rate of progress of historical astronomical research. Early astronomers were extremely lucky that the sensitivity of their eyes was such that they could detect only about 4,500 stars on the whole celestial sphere. Life was made even easier by the fact that only half of these were above the horizon at any one time. These stars clearly did not all have the same brightness, but the range was not huge, the brightest star Sirius (α Canis Majoris) being only about 950 times brighter than the faintest that could be seen. This limited range was such that it seemed reasonable to sort these stars into only six 'importance' categories. These were termed magnitudes and the well-trained eye could distinguish brightness differences of about ±0.1 magnitudes.

The magnitude distribution index was reasonably constant over the range of visible stars. Faint stars far outnumber bright ones. For example the whole sky contains about 3,100 stars with $5 < m < 6$ magnitude, the number dropping to nine hundred and eighty for $4 < m < 5$, three hundred and ten for $3 < m < 4$, ninety-eight for $2 < m < 3$, thirty-one for $1 < m < 2$, and about fourteen for $m < 1$. This greatly facilitated the problem of pattern production and recognition. The mapping of the sky into constellations was relatively easy, this task being greatly helped by the fact that the stars seemed to be distributed randomly across the sky, and not in a regular pattern.

The fact that the number of stars with magnitude m was about 3.2 times greater than the number of stars with magnitude $(m - 1)$ was not only useful, it was also reasonable. This constant factor suggested that the variation of star numbers with brightness might be mainly due to stars having similar luminosities but being at a whole range of different distances, as opposed to stars having a huge range of different intrinsic luminosities but all being about the same distance away. This basic assumption (i.e. similar luminosity) produced a workable cosmic model, and one that enabled greater degrees of complexity to be added later.

Another useful, but slightly less intuitive hypothesis that was proposed during the very early history of Greek astronomy (see, for example Dick, 1982), was that the visible stars in the night sky were nothing more than distant suns. The fact that these stars appeared as point sources of light, as opposed to the large solar disc, and that the constellation patterns of the stars did not perceptibly change from generation to generation meant that they were not just distant suns, but very very distant suns. Astronomers are extremely fortunate that the median distance to the bright, $m < 4$, stars that can be seen with the naked eye is about 39 pc, this being some eight million astronomical units, that is 1.2×10^{15} km. This fact, coupled with the fact the median modulus of the radial velocity is 13.5 km s^{-1}, explains why about 1,800 years had to elapse from the time of the production of the first reasonable stellar catalogue before someone realized that a few of the 'fixed' stars were actually moving.

The supposition that the stars we see are 'suns' was extremely useful during the dawn of astrophysics. Data gleaned from the detailed study of 'our' star could be transposed to its distant stellar neighbours. We must not forget, however, that the median $m < 4$ star has an absolute magnitude of about 0.29 making it about sixty-six times more luminous than the Sun and just over three times more massive. If we compare the median $m < 4$ star with the median member of the *actual* stellar population of the galactic disc the difference is even more stark. Analysis of the data for the one hundred and twelve known stars closer than twenty light years, 6.13 pc[1] indicates that they have a median absolute visual magnitude of about 11.94. The median $m < 4$ star is 46,000 times more luminous than this.

Notice also that the stars we can see with the naked eye appear as single stars. In reality many stars are binaries. There are one hundred and twelve known stars within twenty light years of Earth, and fifty-four of these are single stars, thirty-six form eighteen binaries, eighteen form six triplets, and there is one quadruple group. The average distance between the seventy-nine 'single stars plus groups' is about 2.3 pc. Note that, out of the one hundred and twelve nearby stars only eight fall into the $m < 4.0$ group, these being, in order of distance, the Sun, α Cen, α CMa, ε Eri, α CMi, τ Cet, α Aql, and η Cas. The notion that the visible stars could be other than single Sun-like entities is relatively recent. Telescopic observers of the sky noticed that many stars seemed to be rather close together. In 1767 the Reverend John Mitchell applied statistics to the problem. He calculated that the odds of the six brightest stars in the Pleiades having their observed proximity, if the 1,500 stars of their magnitude had been randomly scattered onto the celestial sphere, was about 500,000:1. The fact that the Pleiades was an actual physical group was confirmed in 1846 when J H Mädler discovered that the Pleiades stars had a common proper motion. In 1779 William Herschel started listing 'double stars' in the hope that their observation throughout the year might lead to a measurement of parallax. A list of two hundred and sixty-nine was produced in 1782. Michell (1784) was firmly convinced that many of Herschel's double stars were actually two stars orbiting a common centre of mass under the influence of Newton's laws of gravitation, as opposed to two stars observed by chance in nearly the same direction. Soon the term 'binary' star was being used for a gravitationally-bound pair.

The concept of randomness is also relatively recent and dates from the time of mathematical physicists such as Siméon-Denis Poisson (1781–1840) who published a book on probabilities in 1837. If stars have been scattered on the celestial sphere in a random fashion and you expect to find λ stars in a specific area of the sky, then the chance P_β of finding β stars in that area is given by $P_\beta = \lambda^\beta e^{-\lambda}/\beta!$. Let us, for example, illustrate the effect of randomness by looking at the bright stars along the celestial equator. This region of the celestial sphere has been divided into forty-eight equal areas, each of one hundred and forty-seven square degrees. These areas are one hour of right ascension across and extend from the equator either up to a declination of +20° or down to a declination of –20°. A count is then made of the number of stars brighter than an apparent magnitude of 4.5 in each area. The average number turns out to be 6.7. The way in which the actual number varies about this average is shown in Figure 11 together with the expected Poissonian distribution if randomness is assumed. Forty-five out of the forty-eight regions obey the Poissonian statistics very well. Three regions contain, however, thirteen, eighteen, and twenty stars, way above the average value of 6.7. The existence of the latter two is way beyond the expectation of a random distribution and this unusual feature of the sky should have been noted by past astronomers. Interestingly, the region with eighteen stars contains the Hyades and the right arm of Orion, and the region with twenty-one stars contains Orion's belt (i.e. $5\text{hr} < \text{RA} < 6\text{ hr}$; $0° < \delta < -20°$). The 'thirteen-star' region is the upper part of the constellation of Orion. The ancient astronomers certainly commented on the fact that the majority of stars seemed to be scattered sporadically but they also noted a few 'clusters'. The Pleiades and the cluster of stars near Algenib (α Per) were obvious.

9 NOTES

1. See, for example, the following web site: http://www.anzwers.org/free/universe/nearstar.html

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