# STELLAR DISTANCES : GALILEO'S METHOD AND ITS SUBSEQUENT HISTORY

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Most early attempts to measure distances of stars were based on one of two methods. The first depended on the assumption that the stars are all of approximately the same intrinsic brightness, and that they differ in apparent brightness only because they lie at different distances. From comparisons of apparent brightness made in the eighteenth century it was thought (correctly) that the nearer stars are a few light-years from us. The second method applied the surveyor's triangulation technique to a baseline consisting of a diameter of the earth's orbit. This avoided the dubious assumption of the first method, but the observations of apparent movements involved were extremely delicate. In Galileo's *Dialogo* Salviati suggests using a distant star as a fixed reference point by which to measure the apparent movement of a near star. For this a criterion of nearness was necessary, and until the early nineteenth century it was usually assumed that near stars are bright and distant ones faint. It then became clear that the magnitude of a star's proper motion provides a more reliable criterion, and this led in the 1830s to the first satisfactory measurements of stellar distances.

The search for an authentic example of annual parallax among the fixed stars has a long history which ended only in the late 1830s. In the last century and a half of this period, from the time of Newton onwards, the search was essentially a quest for factual information: if the earth moves every six months from one side of the sun to the other, then this permits us to observe the stars from a baseline measured in millions of miles; given a length for this baseline, then, provided we can measure the amount by which a star appears to shift during this time, we can calculate by trigonometry the distance which separates the star from us. But before Newton the existence or otherwise of a sensible annual parallax among the stars provided, or seemed to provide, an *experimentum crucis* (in Hooke's phrase[1]) of the hypothesis of the earth's motion about the sun, a test which told against the hypothesis more and more decisively as the measurements involved became more and more accurate. For the Copernicans the matter was urgent, and accordingly, in the 'Third Day' of the *Dialogo*, Galileo discusses promising techniques for making the delicate observations. The ideas he put into circulation were to bear fruit more than two centuries later.

The lengthy discussion among the three friends is characteristically fertile. Salviati gives a careful explanation of the nature of the motion for which we are looking.[2] As for the actual measurements, he points out that a stick set up on a distant hill would be as good as an instrument many miles long.[3] What we must do is to choose a suitable star, and to mark in the plains below the hill the position from which the star in crossing the meridian appears to pass behind the stick. Some time later we are to repeat the observation and again mark the place. If we will continue in this way, Salviati points out, we will obtain a series of marks highly sensitive to any displacement of the star. It is worth mentioning that distant markers to north or south of an observatory were to be used in several places in Britain alone, beginning with St Andrew's, where James Gregory set up a trident on a hill, a mile from his observing room.[4] Gregory, whom we shall mention again, had spent an extended stay in Padua in the 1660s.[5]

But perhaps Salviati's most interesting proposal is for the use of faint and no doubt distant stars as markers by which to detect the apparent motion of bright, and no doubt near, stars.[6] For he does not believe that all stars are equidistant from a common centre, but that some are two or three times as distant as others. Now as we move round the sun a near star will appear to shift more than a distant one, and if the two look to be close together in the sky—that is, if they form a 'double star'—then the difference in their motions should be relatively easy to detect.

Galileo, we notice, makes the reasonable assumption that the brighter stars are nearer than those less bright. Some later astronomers were to interpret this assumption strictly and even quantitatively: a bright star was then *ipso facto* near.[7] But as long as one agreed in general terms with James Gregory, writing in Padua in 1668, that the stars are distant suns and the sun merely our local star, *stella fixa vicina*,[8] there remained the possibility of estimating the comparative distances of the sun and a star (Sirius, say) from a measurement of the comparative brightnesses of Sirius and the sun: thus if the observed brightness of Sirius proved to be one millionth of the brightness of the sun, then its distance could be estimated at one thousand times that of the sun, one thousand being the square root of one million.

The problem here was the practical one of actually comparing two bodies so very different in brightness. Gregory proposed what was to become a popular and successful technique; he compared the light we receive from Jupiter at opposition with the light we receive from the sun, a comparison which depends mainly on dimensions within the solar system and on the ability of the planet to reflect light, and then pointed out that the light we receive from Sirius is rather less than the light we receive from Jupiter at opposition. Using the old measure of three minutes for the solar parallax, and assuming that Jupiter reflects all the light that falls on it, Gregory puts Sirius at 83,190 times the distance of the sun.[9] And he is careful to point out that with more accurate figures the distance would be even greater: as Newton was soon to show, some tenfold greater.[10]

Christiaan Huygens, in his *Cosmotheoros,* used a different technique.[11] He observed the sun through a tiny hole in a disk, and then reduced the light still further by means of a lens, until the observed portion of the sun appeared no brighter than Sirius. In this way he arrived at the modest figure of 27,664 solar distances for the distance of Sirius. But it was Gregory's method of using the planets as intermediaries between the sun and the stars that was to be employed with increasing sophistication during the eighteenth century. In 1744, in a remarkable work that contains the first statement of what we know as Olbers's paradox, Philippe Loys de Chésaux arrived at the figure of 240,000 solar distances on the assumption that the planet, in this case Mars, reflects all its light.[12] Lambert, in his *Photometria* of 1760, gives a table of figures for the various planets and puts the nearest star at 500,000 solar distances.[13] John Michell in 1767 proposes some 440,000 solar distances after making allowance for loss of light.[14] As it happens, Sirius, one of the nearer stars but not the nearest, lies at about 550,000 solar distances; we so find that in the middle of the eighteenth century, long before the measurement of a genuine example of annual parallax, the space that separates us from the nearer stars was surprisingly well understood.

Meanwhile attacks, often with specially contrived instruments, were being made on the parallax of particular stars. In 1674 Robert Hooke published 'An attempt to prove the motion of the Earth', in which he followed a detailed study of the great practical difficulties involved and his method of overcoming them, with a list of no more than four observations which he claimed showed a large annual parallax in the star gamma Draconis.[15] But it was not surprising that many considered that four observations were hardly enough.[16]

More convincing were the series of observations of the pole-star which Flamsteed[17] carried out over a period of seven years and which were published in 1699 in the third volume of John Wallis's *Opera Mathematica.*[18] But, as J. D. Cassini was quick to point out,[19] the motion observed by Flamsteed could not be caused by annual parallax: for at any given time of year the star was displaced in a direction quite different from the one that could be due to parallax.

It was with the intention of confirming Hooke's carefully-contrived observations that Samuel Molyneux began observations of gamma Draconis in December, 1725. He was quickly joined by James Bradley, and within a few days they realized that they, too, were observing changes that could not be due to annual parallax.[20] Bradley's recognition that the changes were due to the aberration of light—in other words, that the light from the star appears to reach us from different directions as the *direction* of the earth's motion alters—represents the first notable by-product of this search for annual parallax. The second came two decades later, when Bradley announced that, even after allowance had been made for the aberration of light, there remained a further variation, and this was due to the action of the moon on the earth which resulted in a nutation of the earth's axis.[21] As for annual parallax itself, Bradley considered that, since he had failed to detect its parallax, gamma Draconis must be at least 400,000 times further than the sun.[22]

This minimum estimate by an observer of great finesse was widely accepted, and it encouraged confidence in the photometric arguments that put Sirius at about this very distance. But the fact remained that the most delicate photometric measurements were still to be interpreted in the light of the questionable hypothesis that the sun is a typical star, and that in spite of Bradley's long years of effort still no actual measurement of parallax had been made. What, then, of the method of double stars, proposed by Galileo and advocated by James Gregory in 1675,[23] by Newton in 1685 (but unpublished in his lifetime),[24] by John Wallis in 1693,[25] and by Christiaan Huygens in the posthumous *Cosmotheoros* of 1698?[26] This, Bradley now believed, offered the best hope of success, and like everyone else he assumed that a double star consisting of one bright (and presumably near) star and the other faint (and presumably distant) would be the ideal object for scrutiny.[27]

We must be careful to note that the method of double stars calls for the observation of pairs of stars in almost the same line of sight from us, and of each pair one star must be near and the other distant: for if both lie at the same distance there will be no difference in parallax for us to measure. That is, the method itself presupposes a criterion for nearness, and it had been plausible to suppose that the near stars are the bright ones. Now, however, a new criterion was emerging. Halley had found that three stars had over the centuries moved relative to the other stars[28]—that the stars were no longer 'fixed'—and his discovery of these three proper motions was later confirmed and other examples added to the list. Surely such stars, whose motion across the sky was appreciable to us, must be among our nearest neighbours!

But for the time being there was no conflict of criteria, for the stars with known proper motions were also among the brightest, and therefore presumed near on both counts. It was from another direction that the threat to brightness as the index of nearness was emerging. In 1767 John Michell pointed out in the *Philosophical Transactions* that the stars occur in the sky in closely-packed groups far too often for pure chance to be the explanation.[29] A random scattering of stars throughout space would not provide so many examples of double and multiple stars. 'And the natural conclusion from hence', he wrote, 'is, that it is highly probable in particular, and next to a certainty in general, that such double stars, etc., as appear to consist of two or more stars placed very near together, do really consist of stars placed near together.'[30] In other words, most double stars are not chance or line-of-sight doubles but pairs of suns associated with each other and lying at the same distance from us—and therefore useless for the measurement of annual parallax.

Michell's work was unknown to William Herschel, then an obscure musician at Bath, when he began not later than January, 1778, to collect double stars with the express purpose of measuring annual parallax.[31] By 1781, when he explained his intentions to the Royal Society before presenting the first of his great catalogues of double stars, Herschel had certainly studied the 'Third Day' of the *Dialogo* with great care.[32] He refers to Galileo's work a number of times, and it may well be from Galileo that he takes his postulate that a star of the *n*th magnitude is just *n* times further from us than a star of the first.[33] This postulate, so implausible in Herschel's draft that it brought protests from the Royal Society Committee on Papers,[34] echoes the passage where Salviati tells his friends that the apparent diameter of a star of the sixth magnitude is one-sixth of the apparent diameter of a star of the first.[35] To Herschel, who believed that one star differed little from the next in actual size and brightness, this would imply that their distances were in the ratio of six to one, as his postulate states.*

It was Nevill Maskelyne, as chairman of the Committee on Papers, who drew Herschel's attention to Michell's 1767 paper with its statistical proof that most double stars are unsuitable for parallax measurements.[37] To this Herschel reacted with characteristic obstinacy and persevered in his programme, only to find twenty years later that in several of his double stars the two members had moved in orbit around each other, exactly as Michell had forecast.[38] Just as Bradley in his failure to measure parallax had earned consolation prizes by discovering nutation and the aberration of light, so Herschel's search had led not only to his early discovery of the planet Uranus but now to the first clues to the interior workings of star systems.

The discovery was bought at a price : Herschel, who was deeply committed to brightness as the measure of nearness, had now seen with his own eyes stars revolving round each other at the same distance from us, even though one star might be much brighter than its companion. He himself managed to disregard entirely this unwelcome fact,[39] but for other astronomers the variety to be found among the stars was becoming evident, as was the need for new criteria of nearness. Matters began to come to a head in 1812 when Bessel drew attention to the enormous speed across the sky of the faint star 61 Cygni, which surely proved it must be very close to us.[40] 61 Cygni (which became known as the 'flying' star) is in fact double, and Bessel went on to

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*On the other hand, in 1783 Herschel tried to publish an explanation of changes in the apparent brightness of stars as due to changes in their distances from us,[36] so that (for example) a new star was one that had moved close to us—an absurd hypothesis, as a reading of the 'Third Day' would have shown.

argue that because the two members of the pair share this common motion they must be physically associated in a single system. He was later to maintain that other nearby stars were *not* physically associated with 61 Cygni because they did *not* share this motion with the two members of the pair. In other words, the presence or absence of proper motion provided the clue not only to which stars were near and therefore likely to show a measurable parallax, but also to which other stars were independent and probably distant and therefore suitable as reference points. In a word, proper motions guided the astronomer in selecting suitable material for study by the double star method.[41] As to brightness as a measure of nearness, by 1833 John Herschel was writing that individual stars may differ from each other in dimensions and in intrinsic brightness in the proportion of 'many millions to one'.[42]

It was in the 1830s that three different stars at last yielded parallactic measurements, and in every case the star was suspected to be near primarily because of its large proper motion.[43] In fact, Thomas Henderson at the Cape of Good Hope in 1832-33 observed alpha Centauri initially for quite other reasons, and it was only after his return to Scotland that the large proper motion of the star led him to re-examine his observations for parallax. Henderson, no doubt well aware of the many mistaken claims made from the time of Hooke onwards, was cautious in publishing his result, and by January, 1839, when he at last announced it to the Royal Astronomical Society[44] he could no longer claim priority: for two months before Bessel had written[45] to John Herschel from Königsberg to tell him of the outcome of his observations of 61 Cygni with the fine Fraunhofer heliometer. Bessel had first used the instrument on this rapidly-moving star in 1834, and he had attacked the problem 'by measuring its distance from two small stars of the 11th magnitude, of which one precedes, and the other is to the northward'—in other words, by the method of double stars, though Bessel, unlike William Herschel, could be sure that the reference stars were not physically associated with the star under scrutiny since they did not share the proper motion of 61 Cygni. In his letter Bessel told John Herschel how his work had been interrupted, so that it was only in 1837 that he had been able to resume it, this time with two different reference stars. Now, October, 1838, he could give the news that his measurements put the star at 657,700 solar distances from the earth.

It was during much the same period, from 1835 to 1838, that Wilhelm Struve at Dorpat made a similar study of the bright star, Vega, again encouraged by its large proper motion and again examining its position relative to other stars.[46] Struve's observations (like Henderson's) were generally considered less convincing than those of Bessel,[47] but these three independent claims made it clear that at long last distances of stars had been measured. Brightness had now taken second place to large proper motion as the main criterion of nearness, but it was fitting that two of the three successful measurements, and in particular the one that carried immediate conviction in the astronomical world, were made by the technique of double stars that Galileo had proposed more than two centuries before.

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[5] *Ibid.*, p. 4.

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[9] *Ibid.*, p. 148.

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