Professor Sir Francis Graham Smith. Not yet, but this one came out of a large survey, and there are a lot more data.

Professor Tayler. What if you relaxed your constraint that neutron stars always have 1·4 solar masses? What would this do to the mass of the companion? Certainly no white dwarf has this radius; is a lower-mass object larger?

Professor Lynden-Bell. It can get as big as Jupiter but no larger.

Professor Sir William McCrea. Does the mass loss lead to the disruption of the binary?

Professor Sir Francis Graham Smith. That depends on the specific angular momentum of the mass being lost.

A Fellow. Is the pulsar rotation axis in the plane of the orbit?

Professor Sir Francis Graham Smith. No, it must be at a considerable angle.

Dr. Marsh. Is the spindown of the neutron star measured?

Professor Sir Francis Graham Smith. No. This is difficult. It is not rapid.

Dr. Marsh. Would you not expect a rapid spindown because of the interaction with the companion?

Professor Sir Francis Graham Smith. Evidently it does not feel the presence of the companion at all.

Dr. Dworetsky. Is the distance known?

Professor Sir Francis Graham Smith. The dispersion measure suggests a distance of 2 to 3 kiloparsecs.

Professor de Jager. Could the companion be a white dwarf with an extended atmosphere?

Professor Sir Francis Graham Smith. Yes. But certainly not a normal white dwarf.

The President. Thank you. The meeting is adjourned until 1988 Friday October 14 at Savile Row.

THE DISTANCES TO THE STARS

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[The Halley Lecture for 1988, delivered in Oxford on 1988 May 3]

Mr. Vice-Chancellor, Ladies and Gentlemen:

In 1718, Edmund Halley published a short note in the *Philosophical Transactions* announcing that, in the course of a redetermination of the rate of precession of the equinoxes, he noticed that the ecliptic latitudes of the four bright stars *Aldebaran*, *Betelgeuse*, *Sirius* and *Arcturus* had apparently changed by a large fraction of a degree since the time of Hipparchus. He reasoned that "*these stars being the most conspicuous in Heaven, are in all probability nearest to the Earth, and if they have any particular Motion of their own, it is most likely to be perceived in them . . .*". On the evidence of this note, Halley is credited with being the first astronomer to detect a secular change in the pattern of the 'fixed stars'. If we examine Halley's note in more detail, however, we find that he was indeed fortunate. One of the four stars, *Betelgeuse* in Orion, we now know to be a distant supergiant with a total proper motion of only three arcseconds per century or a minute in 2000 years! On the basis of modern values of the proper motions, and the secular change in the obliquity of the ecliptic, we find that only for *Sirius* is Halley's assertion numerically reasonable, and also consistent with Tycho Brahe's observation of this star. But the latitudes of *Aldebaran* and *Arcturus*, predicted from modern data for the time of Hipparchus differ by about half a degree from the positions given in Ptolemy's *Almagest*; for all except *Sirius* the modern data have not resolved the discrepancies between the ancient records and modern observations!

As we shall see, proper motions play an important rôle in measuring the distances to the stars, but this had to wait until sufficient data had been accumulated from the mid-eighteenth century onwards.

The most direct method of measuring distance is from the parallactic displacement of a star during the annual motion of the Earth about the Sun. Early attempts to measure parallax were aimed at providing an observational test of the Copernican theory, rather than determining distances of particular stars. Indeed, the first account of an observation aimed at detecting parallax was entitled *An attempt to prove the motion of the Earth from observations*, which was published in 1674 by Robert Hooke.

The attempts to measure stellar parallaxes, from the late seventeenth century until the final success exactly 150 years ago, are familiar to historians of astronomy. During the course of this quest, several very fundamental discoveries were made. In the first part of this lecture, I shall review the highlights of this early period, in order to put current researches into an historical perspective.

Before proceeding with a description of the experiments by Hooke and later astronomers, we must first consider what they were trying to measure. The locus of the apparent displacement of a star on the sky due to parallax is the projection of the Earth's orbit in the direction of the star. Thus, assuming that the Earth's orbit is a circle in the plane of the ecliptic, the parallactic displacement will in general be an ellipse traced out during the year with major axis parallel to the ecliptic. The length of the semi-major axis is the ratio of the radius of the Earth's orbit to the star's distance, and the eccentricity is equal to the cosine of the ecliptic latitude, that is, the angular distance from the ecliptic.

In the latter half of the seventeenth century, astronomers were of course unaware that all stars were subject to an annual displacement due to aberration of light. Since this depends on the velocity of the Earth in its orbit, rather than its position, the locus of the aberrational displacement is a similar ellipse, with a semi-major axis of $20''\cdot5$, but 90° out of phase with parallactic displacement. In the case of *Sirius* for example, the maxima of aberration occur in January and July, whereas the maxima of parallax are in October and April.

Astronomers, however, measure directly, not ecliptic longitude and latitude, but right ascension and declination, since these are obtained from the time and zenith distance at the instant of meridian transit. In principle, it is easier to measure a change in zenith distance than one in time of transit, since the former can be achieved by purely angular measurement, notwithstanding the complications arising from atmospheric refraction, whereas the latter requires an accurate clock. Therefore, for more than a century after the time of Hooke, most of the attempts to detect parallax were from measurements of zenith distance. The amplitude of the displacement in declination varies over the sky because of the eccentricity of the parallactic ellipse, being a maximum at the ecliptic poles. It was therefore necessary to choose stars at high ecliptic latitudes in order to search for parallax.

Hooke was the first astronomer to apply a telescope to the problem of measuring parallax, although there is evidence that his friend Christopher Wren shared his ideas. In his paper, Hooke gives cogent reasons for observing in the zenith in order to minimize the effects of atmospheric refraction, and achieve mechanical stability in his instrument, and describes how he built it in his lodgings at Gresham College. The object glass of 36 ft focal length was fixed in a tube projecting through the roof, and his eyepiece and 'mensurator' were in the basement. Adjusting his mensurator to find the true zenith point from the long plumb-lines was troublesome. He writes: "*With all these difficulties I was forced to adjust the instrument every observation I made, both before and after it was made, which hath often made me wish that I were near some great and solid Tower, or some great Rock or deep well, that so I might fix all things at once, and not be troubled continually thus to adjust the parts of the said instrument;*". Hooke selected the second magnitude star *γ Draconis*; not only is this star very conveniently placed for observation in the zenith in these latitudes, but it also has a high ecliptic latitude so that its aberrational and parallactic ellipses are nearly circular. Hooke recorded four observations, in July, August and October 1669 during which time he observed the declination to *decrease* by about 24″. Then "*Inconvenient weather and great indisposition in my health, hindred me from proceeding any further . . .*"; and subsequently "*an unhappy accident*" broke his object glass so that was that! Hooke thought he had detected parallax; in his own words: "*'Tis manifest then by the observations of July the Sixth and Ninth: and that of the One and twentieth of October, that there is a sensible parallax of the Earths Orb to the fixt Star in the head of Draco, and consequently a confirmation of the Copernican System against the Ptolemaick and Tichonick*".

Hooke's observations cannot be reconciled with aberration, let alone parallax, but his insistence on the suitability of a deep well for stability in zenith observations clearly influenced Flamsteed who attempted similar observations of *γ Draconis* from a well at Greenwich. Only one observation is recorded, on 1679 July 30. The object glass of Flamsteed's well telescope survives to this day, having been presented to the Royal Society in 1737 by Flamsteed's nephew by marriage, James Hodgson, who had been his assistant at Greenwich from 1695 to 1702. It was optically tested in 1956 by Hunter and Martin who found it to be of very poor quality. No doubt this, and, to quote Hodgson, "*the damp of the place*" made Flamsteed abandon the project altogether.

However, this was not the end of Flamsteed's attempts to measure parallax. In 1689 Abraham Sharp built the great mural arc which was to be Flamsteed's principal instrument for measuring star positions for the next 30 years. In a letter to Wallis, who was Halley's predecessor as Savilian Professor of Geometry, dated 1698 December 20, Flamsteed gave an account of his observations of *Polaris*, made with the arc between 1689 and 1697, from which it appeared that the declination observed in winter was some 40″ more northerly than in summer (Fig. 1). He claimed that this annual displacement was due to parallax. But both J. D. Cassini of Paris and Ole Roemer of Copenhagen pointed out that the change in declination observed by Flamsteed could not be due to parallax, since it was out of phase with the annual parallactic variation. Flamsteed had of course observed aberration!

Roemer also found periodic changes in declination, which he attributed to a movement of the Earth's axis. Because of the uncertainty in refraction, however, he considered that declination observations were unsuitable for measuring parallax so he attempted to measure the sum of the parallaxes in right ascension from

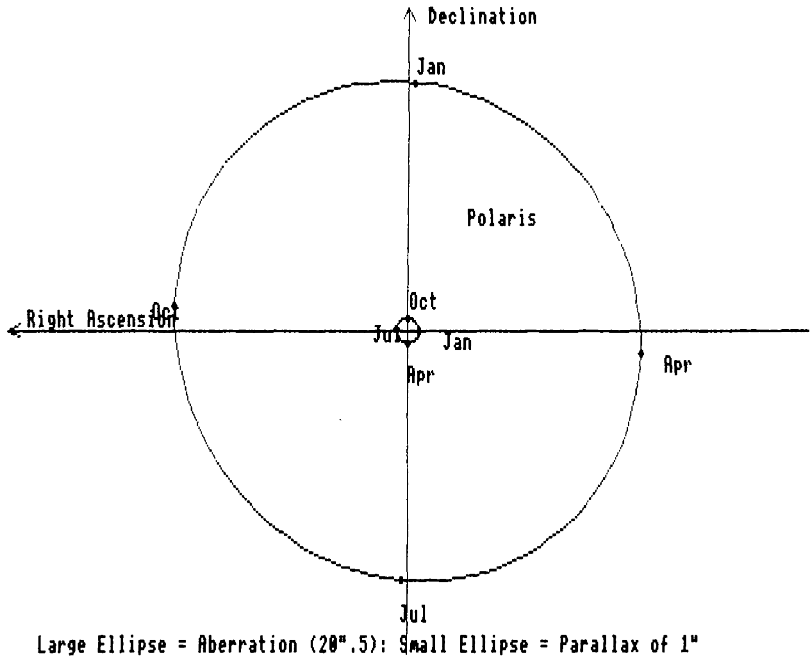

FIG. 1

Aberrational and parallactic ellipses for the direction of *Polaris*. The latter corresponds to a parallax of 1″; the actual parallax of *Polaris* is about 0″·004.

meridian transits of the two stars *Sirius* and α *Lyrae* whose right ascensions differ by about 12 hours. The theory of this approach is straightforward, but Roemer was thwarted by the inadequacy of his clock.

The jewel in the crown of the quest for stellar parallax is surely the discovery of aberration by James Bradley, Savilian Professor of Astronomy. Samuel Molyneux planned to repeat Hooke's observations of γ *Draconis* with a zenith telescope specially constructed for the purpose by George Graham, at his house in Kew. From December 1725, for a whole year, Bradley and Molyneux observed the variation of zenith distance of the star through 40″. From the phase of the displacement it was immediately obvious to Bradley that parallax was not the cause; neither could it be a movement of the Earth's axis (nutation) because the displacement of another star in the zenith, but differing in right ascension by about 12 hours, only showed about half the displacement. Bradley's inspired deduction that the cause was stellar aberration is graphically described in his letter to Halley which appears in *Philosophical Transactions* for 1728. In a postscript, Bradley discusses Flamsteed's observations of *Polaris* in relation to his hypothesis of aberration, and writes "... *The Agreement therefore of the Observations with the Hypothesis is greater than could reasonably be expected, considering the radius of the instrument and Manner in which it was constructed*".

It is somewhat ironic that it was Bradley and not Roemer who discovered stellar aberration. As is well known, Roemer discovered the essential physical phenomenon, the finite velocity of light, from his observations of Jupiter's satellites; he was also aware of the annual variations in the declinations of some stars, both from his own observations and from those of Flamsteed. He was a great maker and user of instruments, but he lacked the scientific inspiration of Bradley.

At the end of his paper, Bradley states "... *it must be granted that the Parallax of the fixt Stars is much smaller than hath hitherto been supposed by those who have pretended to deduce it from their observations. I believe, that I may venture to say, that in either of the two Stars last mentioned, (γ Draconis and η Ursae Majoris) it does not amount to 2″. I am of the Opinion, that if it were 1″, I should have perceived it ...*".

Though Bradley had not found what he had been looking for, he did provide conclusive evidence for the Copernican theory and also set a much tighter constraint on the size of parallactic shift.

Bradley's second great discovery, nutation, was announced in a paper in *Philosophical Transactions* for 1747. Having identified the causes of apparent changes in the co-ordinates of stars to a level of accuracy of about a second of arc, he writes: "*The forementioned Points indeed can be settled only on the Supposition that the angular Distances of these Stars do continue always the same, or that they have no real motion in themselves; but are at Rest in Absolute Space. A Supposition, which though usually made by Astronomers, nevertheless seems to be founded on too uncertain Principles, to be admitted in all Cases. For if a Judgement may be formed with Regard to this Matter, from the result of the Comparison of our best modern Observations, with such as were formerly made with any tolerable Degree of Exactness; there appears to have been a real Change in Position of some of the fixed Stars with respect to each other; and such as seems independent of any Motion of our own System, and can only be referred to some Motion in the Stars themselves. Arcturus affords a strong Proof of this: for if its present Declination be compared with its Place, as determined by Tycho or by Flamsteed; the Difference will be found to be much greater, than what can be suspected to arise from the Uncertainty of their Observations*". Indeed, the declination of *Arcturus* would have changed by five minutes of arc since the time of Tycho, and nearly two minutes since that of Flamsteed. Halley's paper of some 30 years earlier is not even mentioned!

That the parallax of the brightest stars could "*hardly amount to two seconds*" was argued on photometric grounds by the Rev. John Michell in a remarkably prophetic paper in the *Philosophical Transactions* for 1767. His reasoning was based on the calculation of what distance the Sun would have to be at in order to appear to have the same brightness as Saturn. In the same paper he hints at the possibility of luminosity being correlated with colour, "*those which afford the whitest light, being probably the most luminous*", and also argues from probabilities that double stars, and clusters such as the *Pleiades* and *Praesepe*, must be physical systems rather than random line-of-sight coincidences. Another highly significant suggestion appears in the following footnote: "*The apparent change of situation, that has been observed amongst a few of the stars, is a strong circumstance in favour of those stars being some of the nearest to us. This apparent change of situation may be owing either to the real motion of the stars themselves, or to that of the Sun, or partly to the one and partly to the other. As far as it is owing to the latter (which is by no means improbable may in some measure be the case) it may be considered as a kind of secular parallax, which, if the annual parallax of a few of the stars should some time or other be discovered, and the quantity and direction of the Sun's motion should be discovered likewise, might serve to inform us of the distances of many of them, which it would be utterly impossible to find out by any other means*".

However, Michell's demonstration that double stars were most probably physical systems did not deter William Herschel from proposing, in a paper in *Philosophical Transactions* for 1781, to measure the relative parallax of two components of a double star with widely differing apparent magnitudes, on the supposition that the brighter star was much closer than the fainter. The idea of measuring relative parallax was first suggested by Galileo, and it is as well for astronomy that Herschel tried it out, since, as is well known, what he actually detected, at least in some of the stars, was orbital motion and not parallax, as he describes in two papers in *Philosophical Transactions* in 1803 and 1804.

Two years after Herschel's 1781 paper, and some 16 years after Michell's idea of secular parallax, Herschel published his paper on the apparent convergence of proper motions of a few bright stars indicating a motion of the Solar System towards *λ Herculis*. A similar hypothesis was published independently by Prevost in *Memoirs of the Berlin Academy* in the same year. Thus the foundation was laid for the use of proper motions for estimating the distances of stars. Herschel himself exploited the method more than 20 years later in two papers in *Philosophical Transactions* entitled *On the Direction and Velocity of the Motion of the Sun, and Solar System*, in 1805, and *On the Quantity and Velocity of the Solar Motion*, in 1806. In the first of these papers he revised his 1783 estimate of the position of the solar apex. He claimed that about half of the relative displacements which he found in double stars could be accounted for by parallactic motion; this is rather surprising, since he had shown conclusively that the other half could only be explained by orbital motion! In the second paper he used the revised apex to derive the mean secular parallax of Maskelyne's 36 standard stars. Although Herschel refers to the "velocity" of the solar motion, he had no means of converting his value of secular parallax to a linear speed; astronomers had to wait for almost a century before this became possible.

Measurements aimed at detecting parallax were made during the latter half of the eighteenth and the early decades of the nineteenth centuries, by many astronomers, using established techniques of meridian observations. Perhaps the most striking episode during this period was the celebrated controversy between the Rev. John Brinkley, Andrews' Professor of Astronomy in Dublin, and John Pond, Astronomer Royal. Brinkley set out to measure parallaxes of several bright stars with his 8-ft reversible vertical circle at Dunsink Observatory. In 1815 he published a long paper in the *Transactions of the Royal Irish Academy*, giving an account of his observations, and claiming to have measured a parallax of nearly 3″ for *α Aquilae* and parallaxes of 1″ or more for *α Lyrae*, *Arcturus* and *α Cygni*. In *Philosophical Transactions* for 1817, Pond acknowledged that Brinkley's result "*. . . arises from some very permanent cause, and is totally distinct from what has usually been termed error of observation*". He attempted to confirm Brinkley's observations by means of his own, made with the new Troughton mural circle at Greenwich, but soon realized that his observational and reduction procedures, which were aimed primarily at setting up a definitive catalogue of declinations, were not best suited to the measurement of parallax. Nevertheless, he did find discordances between summer and winter observations which could have been due to parallax though he doubted this; these were much smaller than the effects found by Brinkley. He accordingly persuaded the Board of Visitors of the Observatory to provide funds for special telescopes which could be fixed permanently to observe selected stars, on the meridian, specifically for the measurement of parallax. Two such telescopes, of ten feet focal length and four inch aperture, were made, one directed at *α Aquilae* and the other at *α Cygni*. Pond's technique with these special telescopes was to measure with the micrometer, without reference to a plumb-line, the difference of declination between his target star and another star which passed through the field of view several hours away. He thus measured the algebraic difference of the displacements at different seasons and found, in the case of *α Cygni* compared with *β Aurigae*, which differ in right ascension by more than nine hours, a range of only 0″·2 which was hardly significant. One of Brinkley's objections to this method was that an error in the adopted constant of aberration would introduce an error in the difference of declination at the two seasons. This objection was not so strong in the case of Pond's observations of *α Aquilae* for which he used the comparison star *ι Pegasi*, which is only three hours away, but again he could not detect a sensible relative parallax of the two stars. He further analyzed 120 right ascension observations of *α Aquilae*, made with his new transit instrument in 1816–17, again without confirming Brinkley's result for that star. Pond's last words on the subject, in the 1825 *Philosophical Transactions* were: "*Nothing has been farther from my intention, than to place this subject in a controversial point of view. It would be worse than useless so to do, since the difficulty will in the space of a very few years in all probability be satisfactorily explained*".

Within eight years, the observations which were ultimately to vindicate the use of meridian observations to measure parallax were made at the Royal Observatory, Cape of Good Hope, by Henderson, although the results were not published until 1839 in volume 11 of the *Memoirs of the R.A.S.* When Henderson observed the two components of *α Centauri* with his transit instrument and mural circle during 1832–33, they were just two stars on his routine observing programme. It was only afterwards that he realized that, because of their very large common proper motion, they were probably members of a binary system which furthermore might be expected to be close to the Sun. Both co-ordinates were observed differentially, with respect to standard stars. Analysis of the results for both stars in both co-ordinates gave reasonably consistent results. Previous claims from meridian zenith distance or declination observations, for example those by Brinkley, lacked such independent confirmation; it is this which I believe gave credence to Henderson's result.

The climax to the search for parallax came in 1837 and 1838 with publication of Struve's micrometric observations of *α Lyrae* in his *Mensurae Micrometricae* and of Bessel's heliometer observations of *61 Cygni* in volume 16 of *Astronomische Nachrichten*. Both used instruments constructed by Fraunhofer and both were measurements of relative parallax between the target stars and one or two comparison stars. The heliometer, as used by Bessel and later astronomers, is a refractor with its lens cut in half to form two semi-circular objectives which can slide along their common diameter, in any desired position angle; these form two parallel images whose angular separation is measured by their linear displacement.

Bessel was awarded the Gold Medal of the Royal Astronomical Society by the President, Sir John Herschel, in 1841, but in his address on that occasion (*Mem. R.A.S.*, **12**, 453) Herschel stated: "*Should a different eye and a different circle continue to give the same result, we must, of course, acquiesce in the conclusion; and the distinct and entire merit of the first discovery of the parallax of a fixed star will rest indisputably with Mr. Henderson*". Confirmation of Henderson's result came just over a year later from observations of absolute zenith distances of both stars by Maclear, Henderson's successor at the Cape.

C. A. F. Peters, Struve's assistant at Pulkovo, who in 1852 published a long paper in the *Memoirs of the St. Petersburg Academy* describing in great detail all the attempts to measure parallax from the time of Copernicus until 1842, was among others who, during the remainder of the nineteenth century, continued to measure parallaxes by meridian observations. Following the success of Bessel with the heliometer, other astronomers employed the same technique, notably Auwers who used Bessel's instrument at Konigsberg and Gill, first with a 4-inch and later a 7-inch heliometer, at the Cape. With the latter, Gill was assisted by Elkin who subsequently started a programme with the heliometer at Yale. In the literature at this time there are many discordant parallaxes measured by various astronomers; at that time there was little understanding of the nature and sources of systematic errors in this exacting branch of practical astronomy. In his obituary of Gill, written in 1914, Kapteyn praises his parallax work in the following words: "*They are the only reliable determinations of stellar parallax ever made in the Southern Hemisphere. It might almost be said that they are the first parallaxes, or at least the first extensive series of parallaxes, which command the entire confidence of the astronomers*" (*Ap. J.*, **40**, 161).

Exactly one hundred years ago tonight, the Rev. Charles Pritchard, Savilian Professor and founder of the University Observatory, took photographs of *β Cassiopeiae* and *α Cephei* in a programme designed to measure parallaxes by photography. His telescope was the 13-inch reflector which had been made by Warren De La Rue and presented by him to the Observatory. During the previous two years Pritchard had applied the photographic method, using dry plates, to measure the parallax of the components of *61 Cygni* relative to four different comparison stars. The eight different values he obtained were self-consistent, ranging from 0″·42 to 0″·45 (*Oxford Astronomical Observations*, III, 1889). Although these were somewhat larger than Bessel's result there was ample confirmation of such a high value from many other determinations by various techniques. He was naturally very encouraged by this, and decided to start a programme to measure the parallaxes of all the second magnitude stars which could be observed in the latitude of Oxford; he realized that the images of brighter stars might be affected by systematic errors, and in any case these had been well observed by Gill and Elkin.

When I chose my subject for this lecture, I firmly believed that Pritchard was the first to apply photography to the measurement of parallax; and it seemed that this would be a very appropriate occasion to commemorate the centenary of an innovation in technique which was to lead to a dramatic increase in our knowledge of stellar parallaxes. Pritchard certainly was the first to publish his results but he was unaware that some 15 to 20 years earlier, Lewis M. Rutherfurd of New York was taking photographs with a photographic refractor of his own design, using wet plates. These were of many astronomical objects such as the Moon, the Sun and the *Pleiades* and *Praesepe* clusters, and included a few stars for parallax including, of course, *61 Cygni*. Rutherfurd constructed his own measuring engine and measured many of his plates, but did not reduce any measures. All his equipment was donated to the Columbia College Observatory in 1883, to be followed in 1890 by his plate collection. The measurements of *61 Cygni* were reduced by Herman Davis (*Ann. N. Y. Acad. Sci.*, **X**, 123, 1898) who also discussed other determinations, including Pritchard's, which he regarded as untrustworthy, since he claimed to have found numerical errors in *all* of Pritchard's separate values! I have not yet verified these claims. Pritchard's series of 28 stars was also rejected by Kapteyn and Weersma who compiled a catalogue of parallaxes in 1910 in *Groningen Publications*, **24**, on the additional ground that his value for *61 Cygni* was affected by a large systematic error. Since Pritchard's eight quasi-independent values were very self-consistent we must concede that Kapteyn had a point. But rejection of Pritchard's other parallaxes hardly seems fair when we compare his results with modern values, taking into account his quoted errors (Fig. 2). Whether or not these criticisms are justified, Pritchard deserves great credit for pioneering photographic methods for parallax measurement.

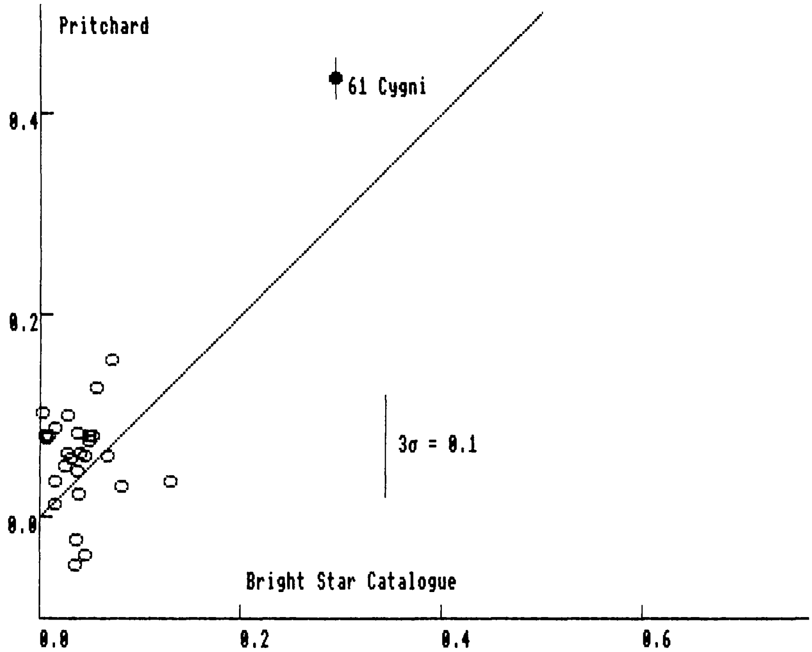

FIG. 2

Parallaxes, in seconds of arc, measured by Pritchard at Oxford, compared with modern values from the *Yale Bright Star Catalogue*.

By the turn of the twentieth century, trigonometric parallaxes had been determined, by various techniques, for fewer than a hundred stars; many of these were of doubtful accuracy. Within the next 25 years nearly 2000 had been measured. The credit for this explosion in data is largely due to one man, Frank Schlesinger, who had worked on some of Rutherfurd's plates when he was a student at Columbia College under Harold Jacoby.

Schlesinger foresaw the enormous potential of photography for the efficient determination of parallaxes, and he first put his ideas into practice at the Yerkes Observatory, where he had the use of the 40-inch refractor.

Before proceeding with an account of the achievements of parallax observers during the first half of this century, I must digress to say something of the techniques introduced by Schlesinger. We saw at the beginning of this lecture, that the parallactic displacement is, in general, an ellipse whose major axis is parallel to the plane of the ecliptic. The amplitude of the component in declination varies widely with position on the sky between the maximum and zero. On the other hand in right ascension the amplitude only varies by about ±4 per cent. On average, therefore, comparatively little statistical weight is added to a parallax determination by measuring the declination component, so, in an age when measurement and computation were extremely laborious occupations, it was a great economy to measure only the one co-ordinate, and to concentrate the observations to the periods around maximum displacement in right ascension.

The measurements on each plate, when reduced with "plate constants" for scale and orientation, give the co-ordinate, Δx, of the target star relative to the centroid of a set of from three to six comparison stars. After the completion of a plate series on one target star, the values of Δx are fitted by a simple least-squares solution to a model giving the relative proper motion and trigonometric parallax of the target star, and a zero point which has no physical significance.

In general, the photographic position of a stellar image depends on many factors, such as its brightness and colour, and the interaction of these with the geometry and the optical-imaging qualities of the telescope and the atmosphere. Schlesinger sought to eliminate these effects by an observing strategy which rendered them as invariable as possible in any one field. In particular, all plates were to be obtained within a few minutes of meridian passage, and the images of bright stars were reduced by means of a rotating sector to be as closely as possible comparable with those of the comparison stars.

After leaving Yerkes, Schlesinger became Director of the Allegheny Observatory at Pittsburgh. There he started a programme of parallax measurements with the Thaw refractor. Several observatories, including Dearborn (Illinois), Greenwich, Leander McCormick (Virginia), Mount Wilson (California) and Sproul (Pennsylvania), undertook programmes on the same general plan. All except Mount Wilson used long-focus refractors; at Mount Wilson, van Maanen used both the 60-inch and the 100-inch reflectors. The selection criteria for these programmes differed between observatories. For instance, the Allegheny programme consisted of bright stars later than B-type, whereas at Greenwich, stars with large proper motion found in the Greenwich Zone of the *Astrographic Catalogue* ($\delta > 64°$) were included in the programme on the 26-inch refractor. These various selection effects have important consequences.

The first fruits of this series of programmes was the appearance in 1924 of the first *General Catalogue of Parallaxes*. By this time, Schlesinger had moved to Yale Observatory as Director, and he set about extending the parallax work to the southern hemisphere by setting up the Yale Southern Station near Johannesburg which was equipped with a 26-inch refractor; this is now at Mount Stromlo in Australia where it is being used for parallax measurement by the McCormick Observatory. The Yale programme was complemented by a similar one at the Cape which was initiated by Spencer Jones in 1926.

The ratio of secular parallax to annual parallax is the linear speed of the solar motion expressed in astronomical units per year. In the early years of this century, the only way to estimate the absolute parallax of comparison stars was from their mean secular parallax, which was assumed to depend only on apparent magnitude and galactic latitude.

Secular parallaxes were studied extensively by Kapteyn and his collaborators at Groningen. In 1901, when Kapteyn's first discussion was published in No. 8 of *Groningen Publications*, the only means of deducing annual parallax from secular parallax was through the trigonometric parallaxes of relatively few stars whose mean secular parallax had been derived from proper motions.

In that year, however, a major advance was made by W. W. Campbell at Lick (*Ap. J.*, **13**, 80, 1901) who derived the solar apex direction and the solar speed in kilometres per second from spectroscopic observations of the radial velocities of 280 stars. Since then it has at least in principle been possible to derive absolute parallaxes, statistically, from proper motions of stars whose kinematics could be obtained from radial velocities. This technique has been and still is used to calibrate the luminosities of particular classes of stars such as Cepheid and RR Lyrae variables which are quite out of range of trigonometric parallax measures.

An important special case of the application of kinematics to the estimation of parallax is that of a moving cluster, and in particular the *Hyades*. It was Lewis Boss who first demonstrated the convergence of the proper motions of stars in this cluster thus enabling the parallaxes of individual members to be obtained from their proper motions (*A.J.*, **26**, 31, 1908). Since then, there have been many investigations of this and other clusters, but it is the *Hyades* which at the present time provides one of the corner stones in the edifice of cosmic distance estimation.

The absolute parallax of comparison stars can now be estimated statistically from their mean apparent magnitude supplemented by colour or spectral type, using a model of stellar distribution in the Galaxy. These corrections to absolute parallax are generally of the order of a few milli-arcseconds, and their likely systematic errors are quite insignificant in relation to the accidental errors of classical parallax measurements.

The measurement of parallaxes became a routine in several observatories in the inter-war years, and culminated in the publication by Louise Jenkins at Yale, in 1952, of the *General Catalogue of Trigonometric Stellar Parallaxes*, and its *Supplement* in 1963. Together, these catalogues contain trigonometric parallaxes of about 7000 stars, the great majority of which are brighter than thirteenth photographic magnitude. They provided astronomers with an extensive body of data which could be used, in principle, for calibrating luminosities and studying the space distribution and kinematics of stars near the Sun. But how useful are these data? Of course, estimates of accidental errors of the individual parallax measurements were given by observers, and the results for the same star at different observatories were combined according to empirical precepts which were intended to reduce all to a common system, that of the Allegheny Observatory.

The first statistical test of the data in the 1952 catalogue was performed by Hertzsprung (*The Observatory*, **72**, 242) who pointed out that the median parallax was $0''\cdot018$ and, from the negative 'tail' of the frequency distribution which was evidently approximately Gaussian, he estimated the average external root mean square error, at least of the smaller parallaxes, to be $\pm0''\cdot016$. This is not to say that many of the parallaxes in the catalogue did not have smaller errors, but it indicated that quite a large amount of the data was of marginal utility. The Jenkins catalogue and its Supplement have provided very fertile ground for more sophisticated statistical examination in recent years.

A revision of the Yale catalogue is now being prepared by Professor van Altena, who informs me that all that remains to be done are the derivation of corrections to absolute parallax and the compilation of notes on individual stars. In addition to including recent measurements, the data in the new catalogue will be on a statistically much sounder basis than those in the earlier edition.

One of the aims of parallax measurements is to investigate the stellar population in a volume around the Sun, the size of which is of course limited by the accuracy of the measurements. In 1957, Wilhelm Gliese at Heidelberg, published a catalogue of stars which were thought to be within 20 parsecs of the Sun; that is, stars with parallaxes larger than $0''\cdot05$. This catalogue contains 915 single stars and systems, with altogether 1094 separate components. A second edition, published in 1969 (*Veröff. A.R.I. Heidelberg*, **22**) contains 1328 single stars or systems with parallaxes larger than $0''\cdot045$. A similar compilation was carried out at Herstmonceux by the Astronomer Royal, Sir Richard Woolley and his collaborators, in 1970 (*Royal Observatory Annals*, **5**); this catalogue extends the limit to 25 parsecs, and includes 1744 systems. Photometric or spectroscopic data have been used to supplement the trigonometric parallax data for a small proportion of the stars in these catalogues. Dr. Gliese and his associate at Heidelberg, Dr. Jahreiss, are currently preparing a third edition of the catalogue of nearby stars; the limit is being extended to a parallax of 0″·04, from the revised Yale catalogue, and it is expected to contain upwards of 3000 systems with about 3500 individual stars.

When parallaxes are known we can, in principle, convert apparent magnitudes into absolute magnitudes, and hence calibrate the colour-magnitude diagram. Great caution must, however, be exercised in interpreting the results from samples such as these, which are defined by a lower limit to *observed* parallax, since the presence of errors of measurement means that there is no sharp spatial boundary. Because volume increases with the third power of the distance, there will be many more stars with positive errors of measurement included in the sample, than with negative errors excluded from the sample. Astronomers have been aware of this effect for many years and have sought to eliminate it in luminosity calibrations by choosing only stars with large measured parallaxes, but in 1974 it was pointed out by Lutz and Kelker (*P.A.S.P.*, **87**, 617) that *all* luminosities derived from parallaxes are biassed to a greater or lesser extent, according to the percentage error in the measured parallax, and they concluded that the bias could not be estimated if the relative error exceeded 17·5 per cent. In round numbers, if we take ±0″·01 to be the typical error of a 'good' parallax in the Jenkins catalogue, this means that the radius of the volume available for selecting stars for direct luminosity calibration is only 17·5 parsecs, which does not give a very interesting sample of stars!

The elimination of bias in luminosity determination is an intricate problem in statistics on which many papers have been published during the past ten years or so. One difficulty is that it is in principle necessary to know the *true* distribution of parallaxes in the sample of stars from which the calibrators are drawn, which is not the same thing as the spatial distribution of these stars, since the various observational selection effects must also be taken into account.

As I have already remarked, some of the major parallax programmes which have contributed to the Jenkins catalogue were based on stars selected on size of proper motion. Such a selection criterion is, of course, very appropriate if the main object is to find stars with large parallax. Indeed this is the reason why Bessel chose to measure *61 Cygni* and Henderson *α Centauri*, both having very large motions. But this criterion favours stars with high transverse velocity, and means that the kinematic statistics derived from these stars will also be biassed. The objective prism surveys by Vyssotsky, who was born exactly 100 years ago this year, and his collaborators at the Leander McCormick Observatory, have found many hundreds of K and M dwarfs whose luminosities, and hence distances, have been estimated spectrophotometrically. By selecting stars for parallax measurement from such surveys one can avoid kinematic bias.

Since the publication of the 1963 *Supplement*, parallax programmes, containing many of the McCormick stars, have continued at a number of the traditional parallax observatories, including RGO at Herstmonceux, and also by a few newcomers to the field; but regrettably the Herstmonceux programme has had to be aborted.

A particularly important programme is now being carried out with a specially constructed 61-inch reflecting telescope at the Flagstaff station of the US Naval Observatory in Arizona. This telescope, which was designed by Kaj Strand who later became Scientific Director of the Naval Observatory, is an *f*/10 paraboloid with a flat secondary mirror. With this large aperture it is possible to observe stars much fainter than those on the more traditional programmes. More than 800 parallaxes have been measured from over 50,000 plates in 20 years; since the emphasis has been on faint stars with large proper motion, the majority of the stars in the US Naval Observatory lists have been lower main-sequence stars and white dwarfs.

Major improvements over the traditional methods are now possible with modern computing and measuring techniques. It is now no longer necessary to limit measurements to a handful of stars on each plate, in one co-ordinate only. It was pointed out by Eichhorn many years ago that the traditional two-step method of computation in which the measurements on each plate are reduced separately to give a Δx, and the results from the plate series then solved for parallax and proper motion, does not make full use of all the information in the measurements. His method, which developed out of his 'plate-overlap' technique for compiling photographic catalogues, makes use of the fact that each star, that is, the comparison stars as well as the target star, must have a unique position, proper motion and parallax which should be solved for, in addition to the plate constants, in a general *simultaneous* solution of all the measurements on all the plates.

I would like to use my privileged position this afternoon to illustrate these new developments by describing an investigation which I and my former colleagues at the Royal Greenwich Observatory have recently carried out with the UK Schmidt telescope at Siding Spring in Australia (*M.N.*, **223**, 629 and 649, 1986). Using the *GALAXY* automatic measuring machine which had been installed at Herstmonceux in 1972, we measured more than 70 plates taken on an area of 20 square degrees near the South Galactic Pole between 1975 and 1981. From these measurements, reduced in the way I have just described, we obtained proper motions, parallaxes and photometry in two colours for about 6000 stars brighter than B magnitude 17·5. We estimate that the true standard deviation of our parallaxes is between $\pm 0''\cdot 012$ and $\pm 0''\cdot 017$ according to magnitude, and likewise that the accuracy of the proper motions is between $\pm 0''\cdot 006$ and $\pm 0''\cdot 008$. The parallax errors are quite comparable with those from the classical refractor programmes and the smallness of the proper motion errors, remembering that we had a spread in epoch of only six years, is due to the large number of plates, which could be measured automatically. The excellence of these data is a tribute to the performance of the Schmidt telescope and to the *GALAXY* machine. Although *GALAXY* was a first generation automatic machine, it was the only one in the UK which was capable of sub-micron precision of measurement, which is essential for accurate astrometric work; no other large machine in this country has yet been shown to equal its performance.

One of our aims was to find out whether the nearby-star catalogues of Gliese and Woolley were complete to their limits of parallax, or whether there could be a significant number of nearby stars omitted because they had small proper motions and had therefore not been selected for parallax measurements in the classical programmes. I must admit that on this point we were not able to detect any deficiency of nearby stars. There is only one star in our area in Gliese's catalogue, with a parallax of about $0''\cdot 08$, which we found without difficulty. There were several with measured parallaxes rather larger than $0''\cdot 04$ but since this represents a level of only 3σ, I prefer to err on the side of caution.

Our main interest has been to use the data, primarily the proper motions, to investigate the space and luminosity distributions of the stars. We were able to demonstrate that a large number of the stars, down to our faintest limit, showed clear evidence for the parallactic motion which is a well-known feature of the bright stars near the Sun. As far as I am aware, this is the first time that parallactic motion has been so clearly established for stars fainter than about fourteenth magnitude, and indicates that these data contain much useful information about the distances and space distribution of these stars. Indeed we were able to derive estimates of the mean luminosities and exponential scale heights for various kinematic groups, from purely astrometric data; these luminosities are in excellent agreement with the standard sequences for dwarf stars and giants in the galactic disc.

We know something of the detailed kinematics and structure of our Galaxy within about a hundred parsecs of the Sun, from the data on the bright stars supplemented by stars with large proper motions. Beyond that, the bare bones of galactic structure have been based on star count analyses and theoretical models. It is only through astrometric investigations such as this one that we will be able to put flesh on those bones. I had hoped that this investigation would be extended to many other fields. This would be a relatively long-term programme, for which the facilities of a national institution such as the Royal Greenwich Observatory would be ideally suited, but in the present situation at RGO this is clearly not possible.

At the IAU meeting in Prague, in 1967, Professor Pierre Lacroute of Strasbourg put forward the idea of a space-borne astrometric telescope. This would be used to make very accurate observations of the relative positions of stars, primarily to set up a reference frame which would not suffer from the defects of ground-based measurements, notably uncertainties in atmospheric refraction and the mechanical distortions of traditional astrometric instruments. If the measures could be extended over a sufficient time interval, both proper motions and parallaxes could also be obtained. The idea was put to the then European Space Research Organization, who had never heard of astrometry! In 1974 a symposium was organized at Frascati, to enable ESRO to assess the scientific significance and the likely support for such a mission. A Mission Definition Study was carried out and the findings reported to a plenary meeting of European space scientists in Paris in 1976 by Dr. Erik Høg of Copenhagen. As I recall, the Space Astrometry project was thirteenth and last in the list of proposed missions!

However, Cinderella does eventually get an invitation to the ball, and accordingly the European Space Agency, which ESRO had become by this time, instituted a full Phase A Study of the project; in fact, two such feasibility studies were carried out, between 1977 and 1979. Then in 1980 the project received the full backing of the various committees of ESA, and was named *HIPPARCOS*. This is actually an acronym for *HI*gh *P*recision *PAR*allax *CO*llecting *S*atellite, which was devised by a French member of the science team, Professor Jean Kovalevsky from Grasse, with apologies to Hipparchus, the 'father' of astrometry, who discovered the precession of the equinoxes and whose star catalogue has come down to us through the *Almagest*. The acronym emphasises that aspect of the mission which concerns us this afternoon, but in fact the satellite will do much more than collect parallaxes. After 1980, detailed planning and design were carried out by ESA in consultation with a team of astronomers, and construction of the satellite is now completed.

The *HIPPARCOS* mission is due to last for two and a half years, during which time sufficient observations will be accumulated to make a very accurate map of the sky, with its changes due to the proper motions and parallactic shifts.

HIPPARCOS will operate from a geostationary orbit. It was due to be launched in July this year, but because of the misfortunes of the *Ariane* rocket programme, this has now been delayed until 1989.

The telescope is a Schmidt with main mirror diameter of 29 cm. In place of the conventional corrector plate, a secondary mirror has been figured to give the required correction; this mirror has then been cut in half, and the two halves cemented together at a mutual inclination of 29° to give two fields of view, each covering an area of 0°·9 square, whose optical axes are separated by a 'basic angle' of 58°.

The satellite spins about an axis normal to the two viewing directions, at a rate of 11¼ revolutions per day. As it spins, stars along a great circle perpendicular to the spin axis are seen first in the 'preceding' field and subsequently in the 'following' field. During the mission, the direction of the spin axis will precess around the Sun some 6½ times per year, at a constant inclination of 43°, so that the sky will be covered many times by a network of great circle scans. The scanning motion will be actively controlled by gas-jets and gyroscopes.

A finely-ruled modulating grid, with lines perpendicular to the direction of scan, is in the common focal plane of the two fields of view. A star image from either field of view gives a modulated signal as it crosses the grid. The main detector is an Image Dissector Tube, or IDT, with an instantaneous field of view of about 30″ in diameter, which can be switched rapidly between stars crossing the field at the same time. The relative phases of the signals, modulo one-grid period, which is just over 1″ on the sky, together with the basic angle, give the angular separations of stars along the scan direction.

In order to derive these angular separations with the required accuracy of a few milli-arcseconds, it is necessary to know the absolute direction of the spin axis to within a fraction of an arcsecond; this is achieved by measuring transits of bright stars whose positions are known *a priori* to a few tenths of a second, across an auxiliary grid which is known as the 'star mapper'. The basic angle itself is calibrated by closing the circle.

The reduction process consists of three main stages. Firstly, the photon counts from the IDT together with the instantaneous attitude of the satellite obtained from the star mapper observations and gyro readings, are analyzed to give the co-ordinates of stars on the grid at specific times; secondly, these grid co-ordinates on a few adjacent great circle scans are combined to give relative angular co-ordinates along some reference great circle with mean errors of from 0″·004 to 0″·012 according to magnitude, and thirdly the zero points of the reference great circles are adjusted and the spherical co-ordinates and displacements for all stars in the programme are derived. Relativistic effects of light deflection and aberration will be verified.

Five astrometric parameters, that is the two co-ordinates at standard epoch, two components of annual proper motion and the absolute trigonometric parallax, will be obtained for each star. Although the expected accuracy will depend to a certain extent on ecliptic latitude and of course on brightness, the average accuracy for stars brighter than ninth magnitude is predicted to be 0″·002 in each of the five parameters.

The data reduction is a highly complex process, involving many teams in Europe. One of the conditions of acceptance of the project by ESA was that there should be two independent data reduction consortia, each of which will receive the raw data from the ground station at Darmstadt, and produce its own catalogue. The rules governing the production of the final published catalogue from the results from the two consortia have not yet been worked out in detail, but the intention broadly is that inter-comparison between them will be used to assess the presence of systematic errors.

The two consortia are FAST (Fundamental Astronomy by Space Techniques), which is led by Professor Kovalevsky, and NDAC (Northern Data Analysis Consortium), under the chairmanship of Dr. Høg. The FAST consortium includes teams from France, Germany, Italy, The Netherlands and USA; NDAC, which is much smaller than FAST, has groups from UK, Denmark and Sweden. The UK contribution is now exclusively from the Royal Greenwich Observatory but during the development stages since 1980 there has been very close collaboration with a group at the Mullard Space Science Laboratory.

In the case of NDAC, the analysis of IDT photon counts and the determination of the satellite attitude is being developed and will be implemented at the Royal Greenwich Observatory, the great circle reduction in Copenhagen at the University Observatory and the Danish Space Research Institute, and the derivation of the final astrometric parameters at the Lund Observatory in Sweden.

Although the data reductions will be performed independently by the two consortia, there has been interchange of simulated data and intercomparisons of data reductions which have proved very fruitful during development, and there will also be regular checks at various stages during the mission.

The selection of programme stars has to satisfy certain constraints. The total number which can be observed in the two and a half year mission is about 120,000, which must be reasonably uniformly distributed over the sky in order to ensure a satisfactory calibration of the basic angle and linkage between the different great circle scans. Not more than ten stars from either field of view can be observed at any one time, so that in crowded areas such as the galactic plane, the Magellanic Clouds and star clusters, only a few representative stars can be selected. Furthermore, because of the small aperture and the scanning motion, only relatively bright stars are observable, the practical limit being about $B = 11^{\mathrm{m}}$. Although it is possible to observe stars as faint as $B = 13^{\mathrm{m}}$, these faint stars require an excessive amount of observing time which is then not available for other stars.

In response to an invitation from ESA, observing proposals were submitted by over 200 individuals or groups, representing countries all over the world, which, with redundancies, included more than three quarters of a million stars! From these proposals, an Input Catalogue Consortium, led by Dr. Catherine Turon of Meudon, has compiled the final Input Catalogue. The positions of all proposed stars have had to be checked, and many new observations have had to be made, either from measurements of photographic plates at Bordeaux, Herstmonceux and Leiden, or special meridian observations with automatic meridian circles on La Palma and Bordeaux. New photometric observations have been co-ordinated at the Geneva Observatory where the magnitudes on the *HIPPARCOS* photometric system, which is a broad band centred between the Johnson B and V bands, and as far as possible the colours, of all programme stars have been determined.

The Input Catalogue consists of two roughly equal components, a quasi-complete list of bright stars, which, besides their intrinsic interest, are required for satellite operation and data reduction, and fainter stars selected from the individual proposals. The apparent visual magnitude limit for the first part depends on galactic latitude and spectral type; for spectral types G5 and earlier it varies between $7^{\mathrm{m}}\cdot9$ in the galactic plane to $9^{\mathrm{m}}\cdot0$ at the poles, and for later types it is 0·6 magnitudes brighter.

Before I say something about what we hope to achieve with *HIPPARCOS*, I would like to mention an additional experiment, known as *TYCHO*, which will be carried out on the same satellite, although it is not directly relevant to the measurement of stellar distances.

The original intention of the star mapper grid was, as its name implies, merely to provide auxiliary data for determination of the attitude of the satellite by observation of bright stars. Each transit of the star mapper provides information on position and magnitude, and it was proposed by Dr. Høg that, instead of wasting the time between the bright stars, all stars which are sufficiently bright should be observed, thus giving homogeneous positions and magnitudes for many more stars than could be included in the main *HIPPARCOS* programme, although with lower accuracy. Furthermore, by inserting a dichroic filter in the beam between the grid and detector, it would be possible to observe each star in two colours. The estimated final accuracy for *TYCHO* is $\pm 0''\cdot 03$ in position co-ordinates and $\pm 0\cdot 03$ magnitudes in each of the two colours for half a million or more stars brighter than tenth magnitude.

What will *HIPPARCOS* contribute to our knowledge of the distances to the stars? We recall that absolute trigonometric parallaxes will be measured with an average accuracy of $0''\cdot 002$ for stars brighter than ninth magnitude. I must emphasize the word *absolute*. With modern ground-based techniques, using fine-grain photographic plates or electronic detectors, relative parallaxes can be measured with accuracies of a few milli-arcseconds, but then there is the problem of deriving absolute parallaxes from these relative measures since the uncertainty in the absolute parallax of the comparison stars is comparable with the experimental errors. This is not the case for the less well measured 'run-of-the-mill' parallaxes of stars in the *General Catalogue* for example. For these latter stars, there will be an improvement of about a factor of five in the accuracy. This means that the distance to which parallaxes can be measured with the same relative error as at present is increased by a factor of five, or the volume available for selecting stars for luminosity calibration is increased by a factor of more than a hundred. The dramatic consequence of this can be demonstrated by computer simulations from what we know statistically about the luminosity distribution of stars near the Sun. This is illustrated (Fig. 3) by a simulation in which the parallax limit is set at $0''\cdot 05$. Compare this with the simulation extending the limit to a parallax of $0''\cdot 01$ (Fig. 4), and we see immediately that the upper part of the main sequence to an absolute magnitude of -1, as well as the red giants from $M_v = +3$ to -2 are well represented. This means that luminosities of stars in these upper reaches of the colour-magnitude diagram will be accessible to direct calibration by means of trigonometric parallaxes instead of by the indirect cluster main sequence fitting procedure.

The advantage of having a large number of stars with well-determined distances are obvious. Not only can reasonably accurate transverse velocities be determined, from which the velocity statistics within a hundred parsecs or so can be studied, but also the number of stars for which masses can be computed will be greatly increased. These will include binary stars with known orbits and also single stars for which the technique developed here in Oxford by Professor Blackwell and his colleagues for estimating angular diameters can be used. But these are topics which deserve lectures on their own, and I shall not pursue them further.

Beyond the limit set by accurate parallaxes, we can still extend our knowledge of distances to the stars by means of proper motions. The proper motions to be obtained from *HIPPARCOS* will not only be of high statistical accuracy but they will be free from the large-scale systematic errors to which the proper motions in even our best ground-based fundamental catalogues are inevitably prone. This is particularly important for the distant, highly luminous stars whose velocities are small, such as early-type main sequence stars and Cepheid variables. Kinematic analyses of the new proper motions, together with existing or new radial velocities should provide much more secure statistical luminosity calibrations, independent of cluster main sequence fitting.

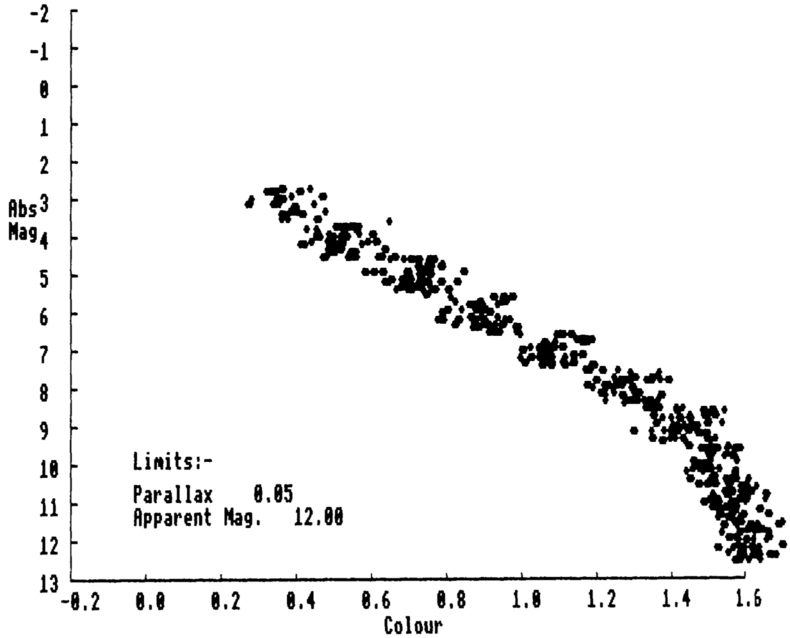

FIG. 3

Computer simulation of the colour-magnitude diagram for a sample of stars with true parallax greater than 0″·05.

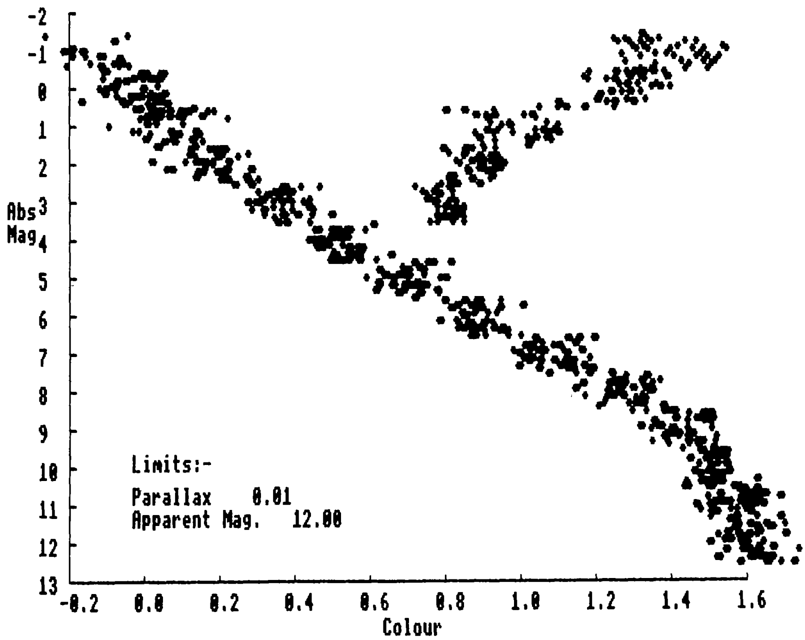

FIG. 4

As Fig. 3 but with parallax limit set at 0″·01.

It is thus at the bright absolute magnitudes that *HIPPARCOS* will have its greatest impact. Indeed, because of the magnitude limitation there will be hardly any late type dwarfs or white dwarfs observable.

Fainter stars will in principle be accessible to measurement from the *Hubble Space Telescope* for which a programme of some 40 stars has been proposed; this is aimed at a definitive calibration of the Population I and II distance scales, and includes members of the *Hyades* cluster, subdwarfs, central stars of planetary nebulae, dwarf novae and stars suspected of having very low mass companions.

At the low luminosities there is much that needs to be done, and which will only be feasible in the foreseeable future by ground-based measurements. From the latest report of Commission 24 of the IAU, which the President, Professor Upgren, has kindly sent me, it appears that regular parallax programmes have been carried out during the last three years in seven American observatories, but in only one other, Shanghai. Electronic detection methods for parallax measurements are being used on several telescopes including the Thaw refractor at Allegheny, the 61-inch reflector at Flagstaff and the 1-metre Kapteyn telescope on La Palma.

But new technology by itself is not enough. In order to make a significant impact on parallaxes, particularly of faint stars, it is essential to give support to long-term programmes to exploit fully both established and new techniques. The US Naval Observatory programme is the only one specifically directed at faint stars, and its success lies partly in having priority use of an excellent telescope for the purpose. This would have been impossible on a common-user instrument. Experience has shown that it is highly desirable that observations from several independent instruments be combined in order to obtain reliable results. The UK has in the past made very significant contributions to the measurement of trigonometric parallaxes, through the support of major programmes in the Royal Observatories at the Cape and at Greenwich; it is therefore particularly regrettable that, because of our way of organizing astronomy at the present time, it is not realistic to expect any major contribution from this country in the foreseeable future.

This brings my story of the distances to the stars up to date, or perhaps even a little beyond, since the fruits of the *HIPPARCOS* and *Hubble Space Telescope* programmes will not be available until the middle of the next decade. But by the end of the present century our enhanced knowledge of the luminosities and space distribution of stars, both from direct measurements of parallax and from proper motions, should provide a new foundation for studies in stellar astrophysics and the structure of our own Galaxy, and for the estimation of cosmic distances and the age of the Universe.