end of the decade. Today there are about 10 000 satellites in space and there could be 100 000 in the next decade. There are currently licences for over a million.

The President. I'll just make a comment. For astronomical things that concern us a lot of mitigation can be done if the design of this craft is right and you have ways of shutting down a radio satellite with interference. A lot of work could be done on treaties if we could agree on the way the satellites are built, in reflectance, interference, and so on. That is one problem that can be dealt with. The debris problem is another matter but in a very serious way.

Professor Mike Cruise. Could I just suggest that people need to learn some lessons from what happened to the IPCC (Intergovernmental Panel on Climate Change)? What they found in their first ten years or so was that they had to be terribly careful about what they said, what graphs they produced, and so on. Not everybody who looks at your pictures or graphs will really understand what you are saying — some of the pictures, such as the re-use of the rubbish in space. I can see the front page of the *Sun* proclaiming "Boffins say a refuse park in space". The trouble is that you do not need a couple of hits like that to damage the case you are making. It's fantastic, but think carefully how pictures can be misconstrued by people, because the IPCC took a long time to learn how much damage was done by the public misunderstanding things they were saying.

Mr. Alexander. That's a fair point. There is a lot of aggressive lobbying but I think science communicators and policy makers felt they were walking on eggshells. We have an opportunity with space not to repeat that same behaviour and learn these lessons.

The President. I think that we are going to draw this to a close. Thank you, Max [applause]. Let me remind you that now, over in Burlington House, there is a drinks reception in the Council Room and you may like to continue some of these questions and comments over there. I give notice that the next open A&G Highlights meeting will be on Friday, March 8th.

THE STRUCTURE OF THE GALAXY AS DESCRIBED IN BRITISH PROFESSIONAL JOURNALS 1820–1920
PART 2: 1906–1920

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Two previous articles considered early papers in British professional journals (primarily *Monthly Notices of the Royal Astronomical Society* and *The Observatory*) which turned out to be about external galaxies[1], and corresponding papers on the structure of our own Galaxy (up to 1905)[2]. Here we extend the latter until 1920 to cover papers up to the culmination of Harlow Shapley's series of papers[3,4] from Mount Wilson which demonstrated essentially the modern picture of the Galaxy, much larger than hitherto believed (in fact, too large), with surrounding globular clusters and the Sun significantly off centre in the disc.

Papers

Moving on to 1906, *The Observatory*[5] carried a Note on a paper by Arthur Hinks originally in the *Proceedings of the Cambridge Philosophical Society*. Hinks suggested that "stars and other bodies forming the Universe are distributed in independent clouds roughly in one plane. … The more distant star-clouds would make the Milky Way proper". The Small Magellanic Cloud was then a star-cloud away from the plane while the "Greater Cloud of Magellan may perhaps be more properly considered a nebula and star-cluster cloud".

From a monumental (715 page) *Memoir*[6] on double stars, as reviewed in *The Observatory*[7], T. E. Lewis deduced that "the [binary] stars around us form a universe very much in the shape of an egg, and that we are not in the centre". The long diameter was 600 light-years and the shorter 300. Unusually, the writer of the review was William Hussey of Detroit Observatory.

A review[8] of a contribution from a less-standard source, a lecture by Kapteyn presented to the British Association in Cape Town, discussed Kapteyn's latest work on proper motions which had led him to propose that most stars belonged to one of two 'star-streams' moving in opposite directions along a diameter of the Milky Way. The reviewer (Hinks) noted "the revolutionary character of this discovery". Arthur Eddington (then Chief Assistant at the Royal Observatory) made similar calculations — and came to the same conclusion[9] — based on Dyson and Thackeray's proper motions measured at Greenwich, also finding a tendency for stars of the same type to be in the same 'drift', but no evidence for them being at different distances[10]. Dyson and Thackeray's work was also reviewed in *The Observatory*[11] by Lewis Boss of the Dudley Observatory in New York, who produced his own catalogue of proper motions, which was in turn used by Eddington[12] in his study of the two drifts.

Eddington presented a similar paper in *Nature*[13], to which Alfred Russell Wallace, the famous naturalist, responded[14], proposing that if the stars were in orbits around some centre, the two streams were merely the consequence of "differential angular motions", in a similar way to the sometimes apparently retrograde motion of planets as seen from the Earth.

Another interesting contribution[15] in *Nature* was by E. H. L. Schwarz who, after suggesting that the 'double drift' was due to orbiting stars on the near side or far side of the Galaxy centre, speculated that the diffuse nature of the Galaxy (with no obvious core) was due to an interaction with the Andromeda Nebula, which he thought to be both external to and more massive than the Galaxy.

By counting stars in representative areas on Isaac Roberts' deepest photographs, J. E. Gore[16] estimated that over the sky the total number of visible stars (down to 17 mag.) should be around 64 million. More intriguing historically, though, was Winifred Gibson's 'Some Considerations regarding the Number of Stars', which is probably the first paper to attempt to apply a modern statistical approach to the stellar system[17]. She used Karl Pearson's new concept of 'correlation', finding no linear correlation between apparent magnitude and parallax and only weak correlation between proper motion and parallax. This suggested that "the system to which the lucid stars belong may possibly be a limited system of a definite and not random structure". (Pearson himself had nine papers in *MN*.)

An entirely different way of demonstrating the local arrangement of stars was presented to the RAS by Mr. T. E. Heath, who created stereographic images of star fields with which the user obtained a pseudo-3D view of the stars with known parallaxes. According to *The Observatory*'s review[18], the "result is most successful. Putting chart number 12 into a stereoscope, one sees Sirius and Procyon apparently hanging in space well in front of all the other stars". A few years[19] later he made a model showing the velocity vectors of stars, even colouring them by stellar type.

W. S. Franks, in a study of the colours and spectral types of stars[20], reiterated earlier results, noting "a curious affinity between Helium stars [B type] and bright line spectra [O type], with the Galaxy … and this becomes still more remarkable when we remember that all the "Wolf-Rayet" stars… all the temporary stars and the majority of short period variables are also in this region". He concluded that the "Galaxy seems to be the plane of origin of some of the most striking phenomena in the stellar universe … [which] must be the result of some grand physical law, at present undiscovered". (Recall that some authors used the term 'Galaxy' to mean the bright ring of the Milky Way, not the whole system of stars.)

Max Wolf[21] reported on photographs of a nebula in the Milky Way (NGC 7023) which he found to be an excellent example of a phenomenon he had observed before, that such nebulae were "encircled by a ring void of faint stars, and that this lacuna is the end of a long starless hole, apparently showing the direction of some unknown cosmic motion". (This work was described in detail when he won the RAS Gold Medal in 1914[22].)

Kapteyn presented his own work at the RAS in 1908 January[23], describing efforts to determine "the number of stars per square degree at any particular galactic latitude", but with no further interpretation. (In what follows we generally pass over papers presenting data on number counts or mean parallaxes as functions of apparent magnitude or Galactic latitude unless there is some significant interpretation in terms of Galactic structure.)

An 'Abstract of a discourse delivered at the Royal Institution' by Kapteyn also appeared in *The Observatory*[24] (produced by S. A. Saunder). Kapteyn had used his proper-motion studies to estimate the local star density as a function of intrinsic luminosity for stars between 0·01 and 100 000 solar luminosities. He suggested that the density was constant ("2000 stars … in a cubic light-century") out to 200 light-years from the Sun but decreased after that. From the "numbers of stars of different magnitudes down to the fourteenth", he deduced that "density-zero, or the limits of the universe" was reached at 30 000 light-years (about 9 kpc) from the Sun. (A longer version appeared in *Nature*[25].)

In addition to points already covered, Eddington's Report to the Council[26] on the 'Stellar Distribution' noted that Karl Schwarzschild in Göttingen had proposed a law of the distribution of velocities of stars which generalized the Maxwellian distribution to an anisotropic system with greater velocities along one axis, *i.e.*, a velocity ellipsoid. Eddington further noted[27] that this might come about through the gravitational contraction of an elongated initial distribution. The major axis would correspond to the direction of the two flows in the Kapteyn model.

H. H. Turner[28] demonstrated that interstellar scattering due to small particles (following Rayleigh's law) could account for the slope of stellar number counts not taking the canonical value 0·6 and being different for visual and photographic magnitudes. This would obviously also affect attempts to determine the density of stars as a function of distance.

In 1909 "Messrs. Hough and Halm" used radial velocities instead of proper motions to support the two-drifts hypothesis[29], with "the relative motion of the two streams … in the plane of the Galaxy, and directed towards its densest part". Eddington — despite them agreeing with his model — nevertheless disagreed[30] with some of their analysis. The following year Hough and Halm extended their analysis[31] to show that while the stars in one stream were consistent with a uniform distribution across the sky, "a chaotic assemblage of stars endowed with no other than chance motions, … in which our Sun is moving with uniform speed", those in the second stream were not, with the Sun evidently shifted off-centre of this drift in the direction towards the North Galactic Pole, the drift itself showing "strong evidence of a structural design", which they identified with 'the Galaxy'. Eddington was more positive about this later work[32], though he was unconvinced about the correspondence of drift 2 with the Milky Way.

Eddington[33] again reviewed associated work from the previous year, particularly Kapteyn's attempt to measure the reddening of more distant stars, from which he had estimated absorption of around 0·5 visual magnitudes per kpc. Pickering had suggested a different slope for the number counts of stars of different spectral types, which, he thought, would not be explained by extinction.

Continuing with 1910, G. J. Burns reviewed[34] his own and other attempts to measure the brightness of the night sky and the total amount of starlight, another proposed means of determining the extent of the Galaxy or Universe. The results suggested a total light equivalent to 1500 to 2000 1st-mag. stars and a surface brightness equivalent to 1–2 5th-mag. stars per square degree at the Galactic Pole. (At the end of the paper, he notes that his observations had been terminated in an unprecedented manner when a burglar made off with his specially built instrument, though "it hardly seems likely that a burglar … would make observations on the amount of "earthlight" in order to select a suitable night for the exercise of his profession".)

From a Note[35] on Barnard's description of his latest photographs of nebulae, it is evident that he now assigned dark areas to absorption, though he still found it "hard to believe in the existence of such [opaque] matter on such a tremendous scale".

In an intriguing battle of mathematical heavyweights, Arthur Eddington (not yet an FRS himself) reviewed[36] a paper by Karl Pearson in the *Proceedings of the Royal Society*, concerning the statistics of observed parallaxes and magnitudes as they related to the distribution of stars in space. For the magnitudes, at least, Eddington's withering assessment was that Pearson's "highly mathematical treatment adds nothing to our knowledge, and only serves to obscure what is a very simple and well known result" (*viz.*, that star numbers did not increase with magnitude as they would for a uniform distribution in the absence of absorption).

Hinks[37] (who had also argued with Pearson) returned to the distribution of nebulae and clusters, reiterating that both planetary nebulae and other gaseous nebulae were concentrated in the Milky Way, as were loose star clusters. He then showed that globular clusters were "contained very nearly in one hemisphere of the sky, whose pole is on the galactic plane in galactic longitude about 300°", thus prefiguring Shapley's famous diagram. (The zero of Galactic longitude was then where the Milky Way intersects the equator, not the — then uncertain, of course — direction to the Galactic Centre.)

In 1911[38], Halm proposed a third drift delineated by 'Orion type' or 'helium' (O and B) stars. He also showed that 'average peculiar speed' increased from

B stars towards later types (this result had also been found by Boss and others[39]), consistent with ideas of equipartition of energy. (At the time, one theory was that later-type stars had cooled down further because they had lower masses.) As usual this was discussed by Eddington at the RAS[40].

Indeed, a summary of the whole question of the structure of the Galaxy, as it was understood in 1911 — at least, by Eddington — was provided in his address to the British Association, reproduced in *The Observatory*[41]. "It is believed that the great mass of the stars (excluding the Milky Way) are arranged in the form of a lens or bun-shaped system, our Sun occupying a nearly central position. Near the Sun, the stars are distributed in a fairly uniform manner, but in the remoter parts of the lens, or perhaps right beyond it, are coiled the great star-clouds which form the Milky Way". (It is intriguing how far the simple, and more or less correct, 18th-Century models of Thomas Wright or William Herschel had gone out of fashion.) Eddington also summarized the work on the two or three drifts. As to the origin of the increasing velocities of later-type (presumed older) stars, he deduced that it must be due to "the central attraction of the universe as a whole, and not the attraction of the immediate neighbours". Surprisingly, he seems not to have considered the possibility that the stellar system could be rotating. ("We might have expected … there would be more definite traces of a centre of gravity, and the velocities would be generally radial".) He did, though, discuss the revived notion that the Galaxy could be a spiral nebula, and that the other spirals "lie beyond the great mass of the stars".

With regards to the supposed third drift, Turner[42], in his 'From an Oxford Note-book', included a quote from W. W. Campbell at Lick, that "an error, of obscure source" was present in the B-star radial velocities, such that, in Turner's words, "the recognition of it is apparently fatal to the fascinating story of great stellar systems of B stars". On the other hand, H. C. Plummer[43] analysed, and confirmed, Campbell's suggestion that A stars had their velocities parallel to the plane of the Galaxy (as the radial velocities were lower in those seen at higher latitude). He later[44] repeated this for B stars. Again, no mention of rotation arises. There was also a Council Report to the RAS[45] covering these topics by H. F. Newall, who noted that Campbell found early-B types were on average 540 pc away but later-B types only 240 pc, while the preference for velocities in the plane was much less for F to K types and least for M stars.

Eddington[46] next produced a mathematical framework to determine simultaneously the distributions of linear motions, angular (proper) motions, and distances of the stars in a catalogue. He concluded that the two- (or three-) stream hypothesis was a better representation than Schwarzschild's ellipsoidal velocity distribution (as did Kapteyn and his assistant Weersma[47], when they presented their method).

Turner[48], though, worried about the apparent inconsistency of thinking of a single stellar system but two intermingled streams. If the system was even roughly a homogeneous sphere stars would be attracted towards the centre. He considered primarily stars falling along near-radial orbits, so that half were approaching the centre and half moving back out, creating the appearance of two streams. (He later[49] noted that stars moving slowly near apocentre could look like a third stream.) He did consider circular motions (for a uniform-density sphere rotation would be like a solid body), either all in the same direction or the "far more likely" case of stars moving in both directions, but largely he preferred near-radial orbits. These might also explain the variation of speed with type, as different-type stars could have originated at different distances from the centre of the primordial nebula and therefore reached different velocities when passing the centre (fairly near the Sun). In addition, Turner tried Plummer's law for the distribution of stars in a globular cluster as a model for the density distribution in the Galaxy but found that the slope of the number counts diminished too quickly with magnitude unless the position of the Sun relative to the centre was carefully adjusted. In passing, he introduced the ideas of dissipation of energy when material in the primordial nebula collapsed towards the centre and reached high density, perhaps leading to star formation, and of anisotropic collapse to a flattened shape. At the RAS, Rev. T. E. R. Phillips[50] queried how Turner's model fitted with the fact that "it is generally held that the Galaxy is not a mere perspective effect, but consists of a ring of clouds at more or less the same distance from us".

Turner[51] next attempted to determine the direction to the centre. Given that the two flows appeared to converge on positions at 6h and 18h RA, he had initially felt that the latter was the direction of the centre, but now (unfortunately) convinced himself that it was nearer the former, in the direction towards Taurus. In his model, intrinsically faint stars were constrained to a sphere near the centre of the system, with the Sun outside it. In response to a talk at the RAS by Plummer[52], the president, Dyson, noted that there now seemed to be three hypotheses, motions parallel to a plane, parallel to a line, or converging to a point.

Reverting to earlier methods, a rather strange paper read by (the equally strange[53]) T. J. J. See to the American Philosophical Society, and partly copied in *The Observatory*[54], used William Herschel's method of comparing the 'space-penetrating power' of telescopes to show that α Centauri should be visible with the 60-inch at Mount Wilson at a distance around 3 kpc. If the most luminous stars were 10 000 times brighter than 'solar stars', then they should be visible at 300 kpc. See also noted that Helium stars would be magnitude 21·1 (about the limit of photographic plates according to Pickering) at about 400 kpc. The reason for assuming that such distant stars really existed was stated to be "the well-known whiteness of the small stars of the Milky Way". By some further geometrical analysis he decided that the thickness of the Milky Way was twenty times the diameter of the ring of Campbell's Helium stars, or around 7 kpc.

Monck suggested[55] that in regions where stars were more thinly spread, mutual gravitational effects would lead to smaller peculiar velocities than where stars were more tightly packed, thus providing a test for a universe with diminishing density with distance from the Sun. The 1913 March RAS meeting[56] then saw both Dyson[57] and Eddington[58] report on their latest efforts to determine the radial distribution of stars based on the distribution of proper motions and an assumed normal distribution of space velocities.

Two interesting notes appeared in *The Observatory*[59]. The first was a review of a paper by Espin in *JRASC* on 'Dark Structures in the Milky Way' which "puts forward with much force the suggestion that there are masses of absorbing matter in space, which give rise to the appearance of dark spaces in the Milky Way" and that "the whole length of the great bifurcation is due to a vast absorption ring". The second was a summary of lectures given by Robert Thorburn Ayton Innes, director of the Union Observatory in Johannesburg, "though his conclusions are in many cases strikingly different from those commonly met with". Innes suggested that "the stellar system, of which the Sun is a member and the Milky Way the girdle, is distinctly limited, and that our telescopes penetrate far into space beyond its boundaries", but without revealing any external objects "such as the spiral nebulae have been suggested to be". He estimated the mass of the Universe to be 441 000 solar masses.

A review[60] of 'Some problems in Astronomy' included a discussion by F. J. M. Stratton of recent papers concerning 'Fixed Calcium Lines', *i.e.*, lines in stellar spectra that appeared not to be associated with the stars themselves. Stratton was inclined to agree with the proposal that they originated in interstellar clouds, since recognized as the first evidence for the interstellar medium.

The ubiquitous Eddington[61] (now Plumian Professor in Cambridge) next considered the dynamics of globular clusters under the assumption that effects between individual neighbours could be neglected and replaced by a smoothed-out density distribution. He estimated the local density to be 10 solar masses in a sphere of radius 5 pc and noted that if "the universe were a globular system of this density, each star would describe an elliptic orbit about the centre of the system in 300,000,000 years", independent of the size of the orbit. He then explored the possible radial and velocity distributions which would permit a steady state of the stellar system.

James Jeans, Eddington's frequent adversary, countered[62] with a study 'On the "Kinetic Theory" of Star-Clusters', considering the opposite extreme of binary interactions only. Assuming the important quantity to be the relative velocity of pairs of stars (taken to be 60 km/sec), he determined that the cumulative deflection of a star's path would only reach 1° after 3200 million years and that a single encounter giving rise to a deviation of 5° would happen only once in 5×10^{12} years. He therefore deduced that "there can be no question of a universe like ours coming to a final steady state such as we are familiar with in the theory of gases", with the relaxation time being of order 10^{14} years.

Plummer[63] returned to the distribution of B stars, finding additional evidence for them lying in, and moving parallel to, the plane of the Milky Way (and with a reasonably uniform density, rather than being in a ring). He favoured later-type stars (of lower luminosity) being in a more spherical distribution with random velocity vectors. After extending the analysis[64], though, he "found it difficult to retain the idea of distinct streams".

Eddington[65], while agreeing that earlier-type stars were steadily more concentrated towards the Galactic plane, consistent with them being more distant and more luminous, rejected this conclusion on the grounds that their 'mean parallactic motion' (motions towards the solar apex) and 'mean cross proper motion' (at right angles to the former) implied that F stars were the nearest and M stars more distant than A stars. He therefore deduced that A stars were genuinely concentrated in the plane while M stars were in a larger spherical distribution (because they were older and had developed larger random velocities). He squared this with the known low luminosities of nearby M stars by noting that Hertzsprung and Russell (the latter in a presentation[66] to the June RAS meeting) had recently suggested dividing M stars into 'dwarfs' and 'giants', so it was the latter which were very distant.

'Mr Jones', the future Astronomer Royal Sir Harold Spencer Jones, similarly found the largest proper motions to be for A5 to F9 stars (which also showed most evidence for streaming), with F and G stars the closest on average[67]. Radial velocities increased steadily for later types. In a separate contribution[68] he reviewed studies of interstellar extinction and reddening but was forced to conclude that the loss of light per unit distance was still largely indeterminate, though "undoubtably very small" (he suggested about 0·5 magnitudes per kpc). Notwithstanding the uncertainty, L. V. King took this a step further[69] and used Rayleigh's theory of scattering to deduce the required density of interstellar gas, assuming it to be composed of molecular hydrogen at standard temperature and pressure. He estimated a value around 10^5 molecules per cubic centimetre or 6300 solar masses per cubic parsec, exceeding the then estimated density in stars by a factor of 10^5.

Eddington produced his usual Report to the Council in 1914[70], noting in addition to the work above, Easton's latest "hypothetical representation of the Galaxy as a spiral" in *ApJ*. Eddington considered it "very instructive, showing how the spiral theory works out in detail". Eddington also reviewed[71] Campbell's book *Stellar Motions* which presented the latest work on radial velocities as a function of spectral type and apparent magnitude and on stars of very high velocity, amongst other topics. Eddington's own book *Stellar Movements and the Structure of the Universe* was reviewed by Dyson[72] and Plummer[73]. At the RAS, Dyson concurred that proper motions implied that M stars were distant and therefore of the giant variety. His star counts and derived parallaxes[74] gave a decline in number density of F and G stars by a factor 10 between 90 and 740 pc from the Sun.

Sydney Chapman and Royal Observatory colleague P. J. Melotte produced an extensive *Memoir*[75] on star counts down to magnitude 17 as a function of Galactic latitude, which Chapman summarized in 'On the Total Light of the Stars' in *MN*[76]. They found the same concentration towards the Galactic plane at all magnitudes. Further, from their (Gaussian) fit to the counts they estimated that they would need to reach a magnitude around 23 or 24 to see half of the inferred total of around 10^9 stars, while half the total light should be contributed by stars brighter than magnitude 10. The total light was estimated to be equivalent to 631 1st-mag. stars (which equated to "an ordinary 16 candle-power lamp at 47 yards distance"). Chapman later reviewed[77] corresponding work by van Rhijn in Groningen and Seares at Mount Wilson, who found instead greater concentration of faint stars in the Milky Way. He agreed with van Rhijn[78] that there had been an error in the Chapman and Melotte reduction (such that the extrapolated total number of stars increased to 3×10^9, half of them fainter than magnitude 25·5). R. J. Pocock[79] also supported the earlier southern-hemisphere result of Kapteyn, finding greater concentration for the fainter stars in the Perth Catalogue.

O. R. Walkey supplied two papers to *MN* in 1914[80], the first on defining the locus of the Galactic plane and the second on 'The Sun's Place within the Star-sphere' which used star counts as a function of Galactic latitude and longitude to find the height of the Sun above the plane (around 40 pc, though not explicitly stated) and distance from the centre (130 pc) of an oblate stellar distribution.

In 1915, Eddington updated his dynamical modelling[81] to show that there existed a density law such that a (spherical) stellar system in equilibrium could possess Schwarzschild's ellipsoidal distribution of velocities (and look like Turner's two or three streams), though the differential equation involved was insoluble. In an illustrative case with the central density seven times higher than near the Sun, the Sun's distance from the centre would be 500 pc and a star falling from near the Sun to the centre would gain a velocity of 36 km/sec. A further paper[82] extended the theory to oblate distributions of stars, the case where the potential was not necessarily just due to the stars themselves, and the addition of rotation.

With colleague W. E. Hartley, Eddington[83] considered tests of the model using radial velocities, finding that the prolateness of the velocity ellipsoid decreased for later-type stars, and the long axis (vertex) agreed with that found from proper motions. He also summarized (at the British Association[84]) the evidence, originally from Kapteyn and Adams (Mt. Wilson), for large-proper-motion stars (presumed nearby, low luminosity) having larger velocities than those of the same spectral type with small proper motion (assumed to be distant, high-luminosity stars), as he and Hartley also found. This allowed three possibilities; (*i*) average velocity decreased with distance from the Sun, (*ii*) velocities decreased with luminosity, (*iii*) there was a correlation between the line-of-sight and transverse components of the velocity. Kapteyn and Adams had suggested (*iii*), though it went against the theoretical preference for a Maxwellian distribution of velocities, but by including other evidence Eddington concluded that (*ii*) was the most likely.

Finally for 1915, Jeans[85] responded to the recent papers by Eddington and Turner with an extensive exercise in statistical mechanics which led him to the rather decisive conclusion, that "star-streaming is evidence that our universe has not yet reached a steady state. It is not, therefore, possible to derive any evidence as to the structure of the universe by combining our knowledge of star-streaming with the assumption that the universe is in a steady state". He did note a "special case", *viz*., "a universe which is rotating as a whole", in which case "the star-streaming must occur in circles round the axis of symmetry of the universe", but dismissed this as "the observed star-streaming is not of the form required". At the RAS, Eddington[86] added that the next question was then "how far it must be from a steady state: with a distribution of mass as found, can we get a Universe in an approximately steady state?".

Harlow Shapley's work made its first relevant appearances in the pages of UK journals in 1916 when Turner[87] reviewed his paper which found negligible reddening towards the stars of M13, Turner noting that this would solve the problem of the huge mass of interstellar matter found by King (above) based on other estimates. (This was not, in fact, the problem with King's calculation, his adopted value of 1·9 magnitudes per kpc not being unreasonable.)

The Observatory[88] reported the claim by Leopold Courvoisier (the chief observer at Babelsberg) in *AN* that stars at the 'front' of the Ursa Major cluster were heading in a slightly different direction to those at the 'back', inferring that they were in orbit around a point 930 pc away towards Cygnus, with a period of 180 million years.

Jeans and Eddington continued to trade papers in 1916. Jeans[89] considered the case where stars were initially in clusters, which then gradually disintegrated *via* interactions, the remnants of clusters appearing as star streams (anticipating, in some ways, the modern picture of the incorporation of satellite galaxies into the Milky Way). Under certain assumptions, he could also generate the law for star numbers and a velocity ellipsoid as observed, though the implication was that our "sub-universe" must have interacted with others. Unsurprisingly the paper generated considerable interest at the RAS[90].

Eddington[91], meanwhile, presented what appears to have been the second — and first generally useful — statement of the virial theorem in astronomy. (Poincaré had presented it earlier but in a not-easily-accessible 1911 monograph.) Eddington applied it to the case of the dissolution of a moving cluster, determining that even a small cluster should be stable for several hundred million years[92].

An idiosyncratic take on the size of the stellar system was supplied by C. V. L. Charlier[93]. By assuming that each sub-type of B stars had a well-defined absolute luminosity (estimated from their proper motions and radial velocities), he determined that 'The Galaxy of the B-stars' declined in density from the centre to zero after "some 150 to 200 siriometers". The siriometer was his own personal unit, a million AU or nearly 5 pc. The centre was supposedly 18·2 siriometers (88 pc) away in the direction of Carina. (In a later presentation to the RAS[94], he did correctly identify the minimum stellar density in the Milky Way towards Auriga, and the maximum in the opposite direction, Aquila/Sagittarius, as indicating the direction to the Galactic centre.)

Charlier was a supporter of the kinetic theory of stellar distributions, but nevertheless disputed[95] Jeans' conclusion (above) concerning the lack of a steady state. Charlier also considered that Turner's Ursa Major stream, for example, could be the remnant of a formerly large compact cluster. In the light of additional observations, in a subsequent paper[96] Jeans accepted some of Charlier's criticisms, suggesting that the Galaxy could have started as a rotating nebula and progressed through a spiral form, "the history of such a system of stars [consisting] of a gradual transition, or more precisely an asymptotic approach, to a state of steady motion of a system of independently moving stars".

Surprisingly, given the endpoint of his study just three years later, Shapley's first contribution in a British journal[97], a criticism of work on star distributions in globular clusters, ended with the statement that "one is naturally led to the hypothesis that the globular clusters are distinct systems, separate from and virtually independent of the galactic system, and some of them, perhaps, not greatly inferior to it in size". (He was at this point using other people's, rather small, estimates of the size of the Galaxy.)

Perrine noted[98] that the apparent centre of the distribution of globular clusters was in the same direction as the "very bright and suggestive region of the Milky Way in Sagittarius and Ophiuchus". He inferred that the clusters were "closely related to the galaxy" and were at "the same order of distance as the more remote portions" of it, though he did not explicitly suggest that they shared the same centre as the Galaxy. In letters to Eddington, summarized in *The Observatory*, Hertzsprung[99] had previously come to the same conclusion as Shapley on the size of globular clusters, but had now changed his mind[100], a measurement of the total light (as opposed to individual stars) implying much smaller and subordinate globular clusters as in Perrine's model.

On the other hand, further work on proper-motion distributions still led Dyson and Thackeray[101] to deduce a small Sun-centred Galaxy; in "the region nearest to us the density is a maximum, and diminishes as we proceed outwards, but much more rapidly in the direction of the galactic pole".

An important point was reached in 1917 November when *The Observatory*[102] carried a review by Eddington of Shapley's "remarkable series of papers", 'Studies of Magnitudes in Star Clusters, I.–VII.'. He discussed first the (lack of) extinction towards globular clusters, then their distances of order 10 kpc as found from the Cepheid period–luminosity relation or brightest-star magnitudes (Shapley gives 6·5 to 67 kpc, with the Sun 13 kpc from the centre of the distribution), and their dimensions and shapes. *The Observatory* had earlier reported on a BAA meeting[103] at which Maunder gave a shorter summary and the work (along with other papers noted above) was included in Eddington's next Council Note[104] on 'Stellar Distribution and Motions'.

This was updated in *Nature* in 1918 May, with a review by Crommelin[105] of Shapley's latest work, in *PASP*, on the distances. Crommelin reported that Shapley had distances for 69 globulars which formed a system with a longest diameter of 300 000 light years (around 90 kpc) and centred 65 000 light years (20 kpc) from the Sun.

A Note[106] in *The Observatory* reviewed work in *ApJ* by Gustaf Strömberg (Mt. Wilson) which suggested that stars at different distances were streaming in slightly different directions, consistent with orbital motion, though the reviewer

— probably Eddington or Spencer Jones, two of the editors — was perplexed by the lower radial velocities for stars nearer the supposed centre (in Carina, a long way from the actual centre).

Meanwhile, there were three 'home-grown' papers of relevance in 1918. Eddington[107] summarized the recent work concerning 'The Dynamical Problems of the Stellar System', specifically the equilibrium of oblate systems with star-streaming. He was sceptical that a suitable state could exist and therefore preferred a model which was still collapsing.

(In a wonderfully self-deprecating review of a booklet by T. E. Heath (see earlier) on 'The Distances, Absolute Magnitudes and Spectra of 734 stars', Eddington[108] had commented that "The general fate of these data is to fall into the hands of some mathematical astronomer, apparently actuated by an irresistible impulse to add things up and take the mean; then comes a sudden jump to mathematical formulae; integrals gather in formidable array, and the error-function makes its inevitable appearance; and so the riddle of the universe is slowly disentangled — or knots itself tighter — to the great satisfaction of those who have any notion what it is all about.")

Plummer[109] returned to star counts across the sky but analysed the density *via* spherical harmonics. He found that the second-order harmonics aligned with the Milky Way axis and with the direction of "greatest mobility" (*i.e.*, star streaming), which he interpreted as the system not being in equilibrium, with "a process of diffusion … tending to bring about a condition of greater uniformity in the galactic distribution". (He also calculated the light from all stars down to magnitude 16 but considered any attempt to extrapolate beyond this was impractical.)

On the other hand, at the end of a paper on orbits of binary stars, Jeans[110] concluded that the only hypothesis which could reconcile the facts of observational astronomy with dynamical theory was that "the present epoch in the history of our universe was preceded by one in which the stars were much more closely packed than they now are", so that more close interactions would have taken place. He supported this by noting that what we now call the Jeans mass would only be similar to the mass of typical stars if the density of the primordial nebula was much higher than the averaged-out density of the present Galaxy. (At the RAS[111], F. A. Lindemann noted that the present density could be suitably higher if there were numerous dark stars.) The dynamics of B stars and short-period binaries (usually early types) suggested to Jeans that these "were perhaps the last stars to be born out of the rotating nebula which we may suppose to have been the parent of our system of stars".

Eddington's 1919 review[112] of 'Stellar Distribution and Motions' included a paragraph on Shapley's determination of the distances of individual Cepheids which ranged up to 4000 parsecs or more on all sides of the Sun "so that they indicate a galactic system of far greater extent than any hitherto discussed". Despite this, Eddington in the following note[113] on 'The Distribution of Globular Clusters' reverted to assuming a local stellar system of diameter "not much more than 1 kiloparsec" which must "lie almost on the circumference of the greater system" outlined by Shapley's globular clusters. Shapley himself discussed the lack of globulars in the "equatorial region" of the Galaxy[114].

Returning to a topic mentioned earlier, John Evershed[115] noted the existence of calcium lines in the spectrum of Nova Aquilae (1918) which had zero radial velocity once the solar motion was accounted for, thus suggesting clouds at rest in the overall stellar system.

Anton Pannekoek[116] disputed Plummer's description of the distribution of stars (above), because of suggested inhomogeneity of the data, and gave a detailed description of the irregular stellar distribution which differed spatially from that of the brightness of the Milky Way. Allowing for the latitude dependence of the counts, he concluded that the dependence on longitude was due to two areas of deficiency, perhaps caused by extinction. Henri Nort[117], whose values Plummer had used, responded and pointed out that Pannekoek's result could also be interpreted *via* an elliptical, rather than circular distribution in the plane, *i.e.*, a tri-axial ellipsoid, as Nort had suggested.

Pannekoek[118] also disagreed with the view of a continuously declining stellar density with distance, returning instead to the model of the Milky Way as a ring of star clouds around the local stellar system. From changes in slope of the number counts towards bright star fields at around 12th magnitude, he deduced that the Milky Way clouds were in the distance range 40 to 60 kpc with a significantly off-centre position for the Sun.

Pannekoek and others generally used Kapteyn's 'luminosity law' (*i.e.*, what is now the stellar luminosity function), a gaussian with a fixed mean value. Halm[119], though, noted that in the general case both the density and the mean absolute magnitude could vary with distance (and direction). Considering the extreme cases of fixed luminosity law or fixed density, from a lengthy general exploration of the theory of star numbers and mean parallaxes as a function of magnitude, Halm concluded in favour of the latter, that is, the density of stars did not change with distance, but rather the variations were due to the luminosity law. (The following year, from a study of binary stars, Jackson and Furner[120] reached the modern conclusion that star numbers, in fact, increased continuously towards fainter absolute magnitudes.)

While Shapley presented the summary of the Mount Wilson work on the structure of the Galaxy in 1919 — a modern-looking disc of much greater extent than the 'local system' around the Sun, perhaps of radius 30 kpc or more with the Sun half-way to the edge, and the surrounding globular-cluster system with diameter of order 100 kpc — this was not actually a particularly defining moment. Indeed, the published version[121] of the 'Great Debate' of 1920 on 'The Distance Scale of the Universe', generally portrayed as concerning the existence of 'island universes', actually largely revolves, especially from Shapley's side, around Shapley's ten-times-greater size for the Galaxy than that still used by Curtis. As for the UK, with Eddington and Jeans now busy with relativity and the internal constitution of stars, there was no mention of Shapley's most recent work at all in 1920, and in fact there was only one paper linked to Galactic structure, Halm's[122] on his third-drift idea. Indeed, the first mention of Shapley's cumulative work came in a short historical piece by Hector MacPherson[123] in 1921, comparing Shapley's ideas with William Herschel's.

The Authors and Reviewers

Note that biographical notes are not included for contributors already included in recent articles[1,2,124].

Thomas Lewis had been an assistant at Greenwich since 1881. As well as observing binary stars he was in charge of the observatory chronometers as Superintendent of the Time Department. He was secretary of the RAS from 1905 to 1909.

Trained as an engineer, William Joseph Hussey was on the faculty at Stanford from 1892 and was Astronomer at Lick from 1896 to 1905 when he moved to Detroit. Like Lewis he spent many years observing a large sample of binary stars.

Lewis Boss was the long-serving director of the Dudley Observatory in New York who produced a notable catalogue of proper motions. He won the RAS Gold Medal for his work on the convergent point of the Hyades. His son Benjamin followed him as director of Dudley Observatory, working on similar topics to his father.

Charles Darwin's original correspondent on the theory of natural selection, Alfred Russell Wallace, had combined his interest in astronomy with his expertise in evolutionary biology in a 1904 book, *Man's Place in the Universe* (written when he was 82), which considered the possibility of life on other planets from a biological viewpoint.

Ernest H. L. Schwarz was a geology professor at Rhodes University in Grahamstown, Cape of Good Hope, and formerly a member of the Geological Survey of Cape Colony. He was particularly interested in the 'planetesimal theory' of the formation of the Earth.

Winifred Gibson was one of Pearson's graduate students at University College, London, and was later a university lecturer. She wrote several further papers related to star counts up to 1915.

Thomas Edward Heath ran the Star Patent Fuel Co. in Cardiff with his brothers and made a number of mechanical inventions allied to his business, also turning these skills to astronomy, for instance, building 'An Equatorial Driven by a Hydraulic Ram'.

Samuel Arthur Saunder was an RAS secretary, also a president of the BAA, and a leading lunar observer. A Wrangler when at Trinity (where he was a successful oarsman), by profession he was senior mathematics master at Wellington College.

Sydney Samuel Hough FRS, 3rd Wrangler and Fellow of St. John's, was appointed Chief Assistant at the Cape in 1898. He followed Gill as HM Astronomer in 1907 and completed two catalogues of fundamental stars and five volumes of the *Cape Astrographic Catalogue* before his early demise in 1923.

Jacob Karl Ernst Halm had a varied career, starting at Strasbourg Observatory in 1889. Six years later he was appointed first-class assistant at the new Royal Observatory, Edinburgh, and then went to the Cape as chief assistant when Hough was promoted, being mainly responsible for the spectroscopic work, though following the Great War he had problems as a German national. He is credited with being the first to suggest a mass–luminosity relation for stars.

Gavin James Burns had a degree from the University of London and worked as a civil servant in the buildings department of the War Office. He contributed papers to the *JBAA* on the distribution of stars and was one of the first to discuss airglow (then called 'Earthlight').

Henry Crozier Keating Plummer FRS had been an assistant at Oxford under Turner, but after a year at Lick in 1912 he became professor of astronomy at Trinity College, Dublin, and Royal Astronomer of Ireland. In 1921 he relinquished this to take a position as professor of mathematics at the Military College of Science at Woolwich. He is probably mainly remembered these days for the Plummer potential for globular clusters. He wrote several books, including the important *Dynamical Astronomy* in 1918. His father William Edward Plummer worked at the Oxford and Liverpool observatories for many years, being director of the latter.

Hugh Frank Newall was also the son of another astronomer, Robert Stirling Newall FRS, and was responsible for running his father's telescope after it was moved to Cambridge in 1890. (He had previously been an experimental physicist.) He was on the RAS council for 43 consecutive years from 1892 (president 1907–09) and wrote the 'Stellar Spectroscopy' report virtually every year from 1898 to 1920. He was awarded an honorary professorship at Cambridge in 1909 and subsequently was director of the new Solar Physics Observatory, continuing one of his main research interests.

Rev. Theodore Evelyn Reece Phillips obtained his MA at Oxford in 1894 and was a curate until appointed vicar of Headley, in Surrey, in 1916. He was an outstanding planetary observer and also worked on double stars. He was director of the BAA's Jupiter section from 1900 to 1933 and president of the RAS 1927–29.

Thomas Jefferson Jackson See obtained a doctorate in Berlin, on binary stars, before returning to the US. Falling out with Hale while at Chicago, he next worked with Lowell — when suspicion over him fabricating results first surfaced — and at the USNO. He later claimed to detect planets around other stars and his "intemperate response" to criticism eventually led to him being banned from publishing in American professional journals (though this did not prevent him making 285 contributions in various places over a 47-year career).

Frederick John Marrion Stratton was 3rd Wrangler (behind Eddington) in 1904 and joined the university observatory in 1906. He was primarily interested in solar physics and stellar spectroscopy, becoming assistant director of the Solar Physics Observatory in 1913. In the Great War he rose to the rank of Lieutenant Colonel, then becoming Senior Tutor at Caius (the posts of Astronomer Royal, Astronomer Royal for Scotland, and HM Astronomer at the Cape were all later filled by his tutees). He returned to the SPO as its director and was RAS president 1933–35.

Harold Spencer Jones followed the standard route from Cambridge Wrangler to Greenwich Assistant, replacing Eddington when the latter returned to Cambridge in 1913. Working on optical design for the Ministry of Munitions during the Great War, he was later primarily interested in the rotation of the Earth. He was HM Astronomer at the Cape from 1923, working on numerous stellar programmes as well as his own Solar System research. Astronomer Royal from 1933, he had responsibility for the move to Herstmonceux after World War II and the planning for what became the *Isaac Newton Telescope*. He was knighted in 1943.

Louis Vessot King, an assistant professor at McGill University in Montreal, then only in his twenties, was considered to be the "foremost mathematical physicist in Canadian history" according to his Royal Society biographical memoir. His main research was in radiative transfer and electromagnetic shielding.

Sydney Chapman read engineering in Manchester before becoming a Wrangler in 1908, and Dyson subsequently appointed him as a Chief Assistant at Greenwich where he was mainly involved with magnetic observations, which led to his later career in geophysics. He became a lecturer in mathematics back at Cambridge in 1914 before professorships in Manchester, Imperial College, and, after World War II, Oxford. Elected an FRS in 1919, he was RAS president 1941–43 (winning their Gold Medal in 1949) and president of the International Union of Geodesy and Geophysics 1951–54.

Philibert Jacques Melotte entered the Royal Observatory as a 'supernumerary computer' in the astrographic department in 1895 when he was 15 years old. Developing expertise in celestial photography, he made his name by the discovery of Jupiter's seventh satellite in 1908, but did not reach the grade of Assistant until 1934, subsequently working on the solar parallax under new AR Spencer Jones.

Pieter Johannes van Rhijn studied under Kapteyn, receiving his doctorate in 1915, and succeeded Kapteyn as professor of astronomy and director of the Astronomical Laboratory in Groningen in 1921. He worked mainly on star numbers and distributions.

Robert John Pocock graduated from Oxford and went on to work at the university observatory. In 1914 he was appointed director of the Nizamiah Observatory in Hyderabad. Much of his work was concerned with proper motions and he notably advanced the work on the astrographic zones which had been assigned to the observatory. Overall he had 16 papers in *MN*. He died of pneumonia after catching influenza in the 1918 Indian epidemic.

Herman Albertus Weersma obtained his PhD in Groningen in 1908 for a thesis on the solar apex, and continued to work with Kapteyn as his assistant after de Sitter moved on. He left in 1912 to become a secondary-school teacher.

Trained as a mechanical engineer at the University of London, before joining the ministry, Rev. Oliver Rowland Walkey was elected an FRAS in 1912 while a lecturer at UCL. By chance he was a fellow passenger of Eddington's (with whom he had corresponded) on voyage for the 1919 eclipse, though he was himself heading for the Amazon as a missionary. In 1940, while in India, he published *Concise General Astronomy* with Harihara Subramania Aiyar. He rejoined the RAS in 1943 and published a third *MN* paper in 1946.

Previously at Uppsala, Carl Vilhelm Ludvig Charlier became professor and director of the observatory at Lund in 1897. He was an Associate of the RAS from 1908 and a member of national academies around Europe. Working first in celestial mechanics and then statistical astronomy, he is now best remembered for his theory of an infinite hierarchical universe.

Trained in Copenhagen, Einar Hertzsprung first worked as a chemist before obtaining a position at Göttingen Observatory under Karl Schwarzschild in 1909. He was at Leiden from 1919 to 1946, becoming director of the observatory in 1937. He is, of course, most famous for his share in the development of the Hertzsprung–Russell diagram. He was the son-in law of Kapteyn.

A former student of H. N. Russell at Princeton, Harlow Shapley is best known for his work using Cepheids to determine distances to globular clusters, and hence demonstrate the large size of the Galaxy, as well as his part in the 'Great Debate' at the National Academy of Sciences, supporting the 'Metagalaxy' against the 'island universe' theory of spiral nebulae. Shapley moved from Mount Wilson to become Director of Harvard College Observatory in 1921 and, having accepted their existence, worked on external galaxies, especially in clusters. Indeed, he was one of the first to use the general term 'galaxy'. His independent political views led to him falling foul of the House Un-American Activities Committee in 1946. Some of his work was carried out with his wife Martha Betz Shapley, who published numerous papers on eclipsing binaries.

John Evershed FRS, RAS Gold Medallist in 1918, was a keen amateur observer and instrument builder before becoming director of the Kodaikanal Observatory in India in 1911. Primarily interested in the Sun, he is best known for the 'Evershed Effect' in sunspots. After returning to England in the 1920s he established a private observatory with a notable spectroheliograph where he continued to work until he was 86. Most of his work was carried out in partnership with his wife Mary.

Anton Pannekoek had been at Leiden Observatory in the early 1890s but after writing for socialist magazines was dismissed for leading a strike committee (he was later a major figure in 'council communism') and moved to Germany.

In Holland when World War I broke out, he worked as a secondary school teacher, being unable to take a position back at Leiden because of his Marxist views. However, he was appointed to a post in Amsterdam and founded their astronomical institute in 1921. Much of his career was involved with the Milky Way but he later switched to stellar astrophysics. He won the RAS Gold Medal in 1951, when he was 78.

Isidore Henri Nort was a PhD student at Utrecht and the work referred to was from his thesis, published as *The Harvard Map of the Sky and the Milky Way*. He joined the RAS in 1922 when working as a teacher in Gouda.

Herbert Henry Furner started at the Royal Observatory as a supernumerary computer in 1889 and joined the permanent staff in 1897. Making double-star observations, he took over the work with the 28-inch telescope when Lewis retired.

Conclusion

From the above it is clear that interest in the structure of the Galaxy was high in the fifteen years up to Shapley's key papers. In total there were 137 relevant contributions in *MN*, *Memoirs*, and *The Observatory* (also including a few in *Nature*) or more than nine per year. This compares to 96 contributions, or a touch over one per year on average before this[2]. Authors and reviewers since 1906 numbered 47, 30 of them from the UK (though not necessarily working there) more than 20 of whom can be counted as professionals. This is rather different to the case of papers on extragalactic systems, of which there were only 28 in the years considered here[1] with only five UK professionals contributing — stars were considered more valid subjects for study at the major observatories.

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REDISCUSSION OF ECLIPSING BINARIES. PAPER 22: THE B-TYPE SYSTEM MU CASSIOPEIAE

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MU Cas is a detached eclipsing binary containing two B5 V stars in an orbit of period 9·653 d and eccentricity 0·192, which has been observed in seven sectors using the *Transiting Exoplanet Survey Satellite* (*TESS*). We use these new light-curves together with published spectroscopic results to measure the physical properties of the component stars, finding masses of $4{\cdot}67 \pm 0{\cdot}09$ $M_{\odot}$ and $4{\cdot}59 \pm 0{\cdot}08$ $M_{\odot}$, and radii of $4{\cdot}12 \pm 0{\cdot}04$ $R_{\odot}$ and $3{\cdot}65 \pm 0{\cdot}05$ $R_{\odot}$. These values agree with previous results save for a change in which of the two stars is designated the primary component. The measured distance to the system, 1814 ± 37 pc, is $1{\cdot}8\sigma$ shorter than the distance from the *Gaia* DR3 parallax. A detailed spectroscopic analysis of the system is needed to obtain improved temperature and radial-velocity measurements