6 Astronomy in the Time of Pannekoek and Pannekoek as an Astronomer of his Times

Robert W. Smith

Abstract

The astronomical enterprise underwent enormous changes during Pannekoek's lifetime, including, most importantly, in terms of the technical content and practices of the science, the rise of astrophysics. I suggest that the history of astrophysics between the 1860s and early 1950s can be divided roughly into three stages and that in his later career Pannekoek is best seen as a 'third-stage' astrophysicist. The institutional landscape of astronomy was also transformed during Pannekoek's lifetime, most tellingly with the emergence of the United States as the leading nation for observational astrophysics. However, in the Netherlands, J.C. Kapteyn had shown that it was possible to be an active astronomer without a telescope and Pannekoek would do the same, and fashioned a successful career as an interpretive and theoretical astrophysicist.

Keywords: Anton Pannekoek, positional astronomy, astrophysics, Meghnad Saha, Jacobus C. Kapteyn, galaxy

Introduction

In the period between 1873 and 1960 – the span of Anton Pannekoek's lifetime – the accepted body of astronomical knowledge grew enormously, which coincided with an expansion in the sort of knowledge astronomers regarded as appropriate to pursue. Astronomy in the Netherlands and elsewhere underwent a series of institutional, social, and economic changes too, with the most striking developments in the United States.

Tai, Chaokang, Bart van der Steen, and Jeroen van Dongen (eds), *Anton Pannekoek: Ways of Viewing Science and Society*. Amsterdam, Amsterdam University Press 2019
DOI: 10.5117/9789462984349_CH06

In this chapter, I will examine essential elements of these shifts, and in so doing I will consider two central problems: What counted as both proper and legitimate astronomy? How did astronomers attempt to reveal the size and structure of the Milky Way? Addressing these two questions will, I argue, help bring aspects of astronomy in the time of Pannekoek into focus that were significant for his career. Other scholars, including in this volume, have examined Pannekoek's astronomical career from various perspectives, including perhaps most fruitfully the investigation by Tai and van Dongen and Tai of the epistemic values exhibited in that life's work.[1] Here the emphasis will be on the changing nature of the astronomical enterprise so we can better understand the institutional possibilities and limits that Pannekoek both confronted and shaped, as well as the effect of new conceptual tools and resources.

Pannekoek, we will see, was doubtful about the broader ambitions of the statistical astronomers who sought to model our galactic system. He showed his willingness to adopt new ideas on the structure of the Galaxy when in 1918 he sided with Shapley when Shapley advanced the controversial 'Big Galaxy' thesis. An advocate of the tight linking between astronomical observation and theory, Pannekoek also enthusiastically embraced and applied atomic theory and quantum mechanics to help develop a new sort of astrophysics in the 1920s. He would be one of the earliest and most successful practitioners of what we will describe as 'Third Stage Astrophysics'. In his application of the latest physical theories to the interpretation of stellar spectra, Pannekoek, then, would fashion himself very much as a model of a modern astronomer.

What is Legitimate Astronomy? Astrophysics

The notions of what counted as legitimate astronomy for many astronomers, though certainly by no means all, were greatly expanded in the middle of the nineteenth century by the rise of what would come to be known as 'astrophysics' (a term usually credited to Johann Carl Friedrich Zöllner writing in 1865). To see what changed, it is helpful to refer first to John Narrien's *An Historical Account of the Origin and Progress of Astronomy* (1833). Narrien, for many years a lecturer in mathematics at the British Royal Military College at Sandhurst, painted a clear picture of the advances

I am very grateful to Chaokang Tai and David DeVorkin for helpful comments and discussion on earlier versions of this paper.

1 Tai 2017; Tai and van Dongen 2016.

still to be expected from astronomy. According to him, the application of human ingenuity to astronomy would 'be able to accomplish little more than an improvement in the means of making observations, or in the analysis by which the rules of computation are investigated'.[2] At a time when the first reliable parallax determinations to a distant star were still several years away, and so the only star whose distance was known to any degree of accuracy was the Sun, Narrien reckoned the future of the discipline was decidedly limited. That was not because it had failed. To the contrary, it was because astronomy had reached a very high degree of refinement. As William Whewell, one of the great polymaths of the nineteenth century and the person who coined the term 'scientist', put it in the same year as Narrien's book was published:

> Astronomy is not only the queen of sciences, but, in a stricter sense of the term, the only perfect science; – the only branch of human knowledge in which particulars are completely subjugated to generals, effects to causes [...] and we have in this case an example of a science in that elevated state of flourishing maturity, in which all that remains is to determine with the extreme of accuracy the consequences of its rules by the profoundest combinations of mathematics, the magnitude of its data by the minutest scrupulousness of observation.[3]

For Whewell, Narrien, and others with a professional stake in astronomy, the aim of the science was to track the movements of objects in the solar system and then reduce these motions to order by use of Newton's law of universal gravitation. In this vision of the science, the stars were of importance because they provided a background grid against which the motions of planets, minor planets and comets could be plotted. The physical nature of astronomical bodies was hardly the concern of professional astronomers. As Friedrich Wilhelm Bessel, probably the leading astronomer in the world at the time, put it in 1832:

> What astronomy must do has always been clear – it must lay down the rules for determining the motions of the heavenly bodies as they appear to us from the earth. Everything else that can be learned about the heavenly bodies, e.g. their appearance and the composition of their surfaces, is certainly not unworthy of attention; but it is not properly of astronomical interest.[4]

2 Narrien 1833, 520.
3 Whewell 1833, xiii.
4 Quoted in Hufbauer 1993, 43.

Agnes Clerke, the well-known historian and astronomical popularizer, succinctly summarized matters in 1885 in her account of early nineteenth-century astronomy:

> The astronomy so signally promoted by Bessel – the astronomy placed by Comte at the head of the hierarchy of the sciences – was the science of the *movements* of the heavenly bodies. And there were those who began to regard it as a science which, from its very perfection, had ceased to be interesting – whose tale of discoveries was told, and whose farther advance must be in the line of minute technical improvements, not of novel and stirring discoveries.[5]

Clerke's claim does not mean that there were no changes in the methods and procedures of positional astronomy in the nineteenth century. Observatory practice became increasingly routinized as a consequence of both novel forms of mechanical technology, the chronograph most notably, and new versions of what can be described as organizational technologies. These shifts also meant new sorts of observers, as Kevin Donnelly has emphasized.

> At the forefront of both of these developments were observatory directors like George Biddell Airy, Adolphe Quetelet and Friedrich Bessel, who simultaneously revolutionized the practice of astronomy and created entirely new kinds of scientific labour that demanded patience, discipline and attentiveness in place of open-ended observation, reflection and creativity.[6]

At the end of the nineteenth century, when Pannekoek began his training in astronomy, the view of positional astronomy as the only legitimate form of the discipline seemed exceptionally narrow to many, but far from all, astronomers. The critics of astrophysics included, as we shall see, the director of the Leiden Observatory during Pannekoek's time there. The rise of astrophysics from around 1860 and the efforts of the first generation of astrophysicists to chart the spectra of celestial objects, served to produce a new body of knowledge of the heavens. In time, the pursuit of this knowledge would drive the reconstitution of astronomy. Initially, however, the old-style positional astronomy and the newer astrophysics were separate, so that it is misleading to talk about the pre-existing astronomy being 'transformed

5 Clerke 1885, 185; emphasis in the original.
6 Donnelly 2014, 3. See also Schaffer 1988; and Smith 2003.

by the emergence of astrophysics'.[7] Astrophysics instead owed its birth to developments in experimental spectroscopy that sprang from studies in physics and chemistry.

The researches of the chemist Robert Bunsen and the physicist Gustaf Kirchhoff at the University of Heidelberg provided the initial impetus for this occurrence. In the late 1850s, they demonstrated to the satisfaction of other practitioners that particular sets of spectral lines are associated with particular chemical elements and compounds and also explained how such lines are produced.[8] Remarkable and what, by earlier standards, seemed like almost miraculous powers were now handed to students of celestial objects. As one enthusiast for this novel sort of research wrote:

> The physicist and the chemist have brought before us a means of analysis that [...] if we were to go to the sun, and to bring away some portions of it and analyse them in our laboratories, we could not examine them more accurately than we can by this new mode of spectrum analysis.[9]

Mainstream astronomers, however, sometimes dismissed, ignored or were very slow to warm to the new astrophysics.

The use of photography, especially before the introduction of the dry plate in the years around 1880, was also widely seen by many professional astronomers as problematic. As the leading American positional astronomer (and later discoverer of the two moons of Mars) Asaph Hall explained in 1866:

> For one, I shall be glad to see improvements in methods of observing, but for a very large part of the accurate work of astronomy, I don't yet see how photography is to help much [...] It seems doubtful whether it is well to insert such a method between the observer and the result, since new sources of error are brought in.[10]

The suspicious if not hostile attitude towards the newer developments that were held by many positional astronomers meant that the first generation of astrophysicists and astronomical photographers were usually not 'mainstream' positional astronomers who had expanded their interests. One result of this situation was that until the 1890s, talented and driven

7 Lankford 1997, 36.
8 See, for example, Meadows 1984b; 1984a; Becker 2011; and Hentschel 2002.
9 de la Rue 1861, 130.
10 A. Hall to C. Peters, 19 April 1866, quoted in Rothenberg 1974, 6.

practitioners could pursue astrophysics and astronomical photography at the cutting-edge of research even without an extensive mathematical training or very costly equipment or a professional position. Further, astrophysical investigations in the first two or three decades of the new discipline were usually not driven by specific theoretical problems.[11] Instead, they were commonly surveys of stellar spectra or the detailed investigation of the spectrum of a single object, albeit often with the vague hope that such studies might lead in time to an understanding of the evolution of nebulae and stars. Thus both positional astronomers and astrophysicists tended to be, by later standards, very conservative in their scientific goals.

By the early 1890s, astrophysics had nevertheless become much more of a professional activity than it had been even a decade earlier. New sorts of astronomical observatories were also becoming more common. The focus of traditional observatories was positional astronomy. Their telescopes and ancillary instruments were chosen accordingly to centre on accuracy rather than light grasp, and so observatory directors emphasized transit instruments.[12] In the closing decades of the century, however, new astrophysical observatories were established, and some traditional observatories also added astrophysical researches. In 1874, Kaiser Wilhelm I founded the Potsdam Observatory, and it became the first state-sponsored astrophysical observatory. Others soon followed at Meudon in France as well as the Solar Physics Observatory at South Kensington in London.[13]

These developments had relatively little impact on the activities of the Leiden Observatory. At the turn of the century, it was the largest and best supported of the astronomical institutions in the Netherlands and Pannekoek completed his PhD there in 1902 on the light curve of the variable star Algol.[14] After 1899, he also served as the third observer at the Observatory, the lowest of the institution's professional positions, but it was a permanent post. Pannekoek's principal work, however, entailed making and reducing meridian observations to determine stellar locations in very much the old style. The work at Leiden under the leadership of the two brothers

11 There were exceptions of course, and perhaps the leading counterexample is provided by the investigations of Norman Lockyer.

12 Dewhirst noted that earlier in the nineteenth century, in 1843, readers of the *Penny Cyclopedia* who searched for 'Observatory' were directed to 'Transit instrument': Dewhirst 1985, 150.

13 Herrmann 1975; Laurie et al. 1984. On the establishment of the Solar Physics Observatory at South Kensington, see Meadows 1973.

14 On the history of the Dutch astronomical community in the twentieth century, see, among others, van der Kruit and van Berkel 2000; Baneke 2010; and 2015.

E.F. and H.G. van de Sande Bakhuyzen, neither of whom thought much of astrophysics, was also regimented (Pannekoek wrote his dissertation under H.G. van de Sande Bakhuyzen). Such labour was not to Pannekoek's taste, particularly as he struggled to see the social worth of the positional astronomy done at Leiden. In what is now a well-known quotation, he recalled this time:

> In this environment, where everything happened in the traditions of twenty or thirty years earlier, where there was only endless computation and without anything ever being finished, where the new ways of astronomy were hardly appreciated, all enthusiasm must eventually disappear. Later, [Jacobus C.] Kapteyn once remarked to me: I never understood how you kept up with it so long. [...] I dreaded every Monday morning, when I had to attend the weekly conference in the director's office, where there would be some chatter, and every one mentioned what they had done that week – or invented something – and I realized that every week was in large measure the same, just trickled along a bit. I then always felt a smell around me like in catacombs, of deadly rigidity and boredom.[15]

For some of the lower-level practitioners, positional astronomy, even when there was a clear direction and programmes were accomplished, *was* boring in and of itself,[16] and this picture of Leiden, with the complaint about unfinished work, reveals no sense of accomplishment lifted the tedium for Pannekoek.[17] Pannekoek's decision in 1906 to move from Leiden to Berlin to teach Marxism at the new party school of the Social Democratic Party of Germany (Sozialdemokratische Partei Deutschlands, SPD), therefore, has to be seen in the light of both his rejection of what struck him as the stultifying sort of astronomy that constituted his working life at Leiden as well as his political commitments.

15 Quoted in van der Kruit 2015, 582.

16 See Donnelly 2014.

17 The dreariness of meridian observations was also the key point of a story recounted in 1943 by Otto Struve, then a prominent astronomer and the director of the Yerkes Observatory as well as the Macdonald Observatory in Texas. According to Struve, in 1913, he was aboard a German train returning from a meeting of the *Astronomische Gesellschaft* along with an astronomer he called 'Dr X… an assistant in a German observatory' who had worked on a routine programme with a meridian circle. 'His appointment', Struve recalled, 'had expired on December 31, and he was telling with considerable delight how at the exact second of midnight he had interrupted the transit observations of a star and written *finis* in the official record-book.' See Struve 1943, 475. Lankford also told this story in Lankford 1997, 400.

A Transition

In the early 1910s, then, Pannekoek was in Germany and engaged principally in very different activities than astronomy. But at the start of World War I in the summer of 1914, he was on holiday in the Netherlands. With the outbreak of hostilities, Pannekoek was not allowed to remain in Germany, and so he turned to teaching physics at secondary schools to make a living. When Willem de Sitter assumed the directorship of the Observatory at Leiden in 1918 (he had been a professor of astronomy at Leiden since 1908) after the death of E.F. van de Sande Bakhuyzen, he, as is now well known, tried hard to appoint Pannekoek as one of two assistant directors at the Observatory. Pannekoek, de Sitter thought, should be placed in charge of positional astronomy. If Pannekoek had secured a position at Leiden, he would have had access to working telescopes and significant resources. But despite de Sitter's strong support, Pannekoek, as described elsewhere in this volume, was not appointed because his political views were not acceptable to the incoming government of conservative Christian Democrats led by Charles Ruys de Beerenbrouck that took office in September 1918.[18]

Politics mattered again when in 1920 the University of Amsterdam appointed Pannekoek to a post. The university, as Pyenson has explained, was 'a municipal institution, and so all appointments came at the pleasure of the B & W (*burgemeester en wethouders*), or mayor and town council. In the 1920s, the B & W were stoutly socialist, to which fact Pannekoek, as a long-time left-wing politician, owed his own appointment.'[19] Pannekoek had an astronomical position, but at an institution with no functioning observatory and few resources. He, therefore, confronted a very similar situation to the one J.C. Kapteyn had found himself in when he assumed the professorship of astronomy and theoretical mechanics at Groningen in 1878.

Kapteyn, too, had inherited no staff or facilities. He tried to found an observatory, but, in the face of opposition from Leiden and Utrecht, which already had observatories, and a government unwilling to fund another, he did not succeed.[20] Kapteyn instead made himself relevant by engaging in collaborative efforts with other astronomers. While he was never able to establish an observatory, he did found an 'Astronomical Laboratory'. Aided

18 W.R. de Sitter 2000, esp. 85-93; Baneke 2005; 2010, 170-173; and his 'Pannekoek's One Revolution', in this volume, 87-108.

19 Pyenson 1989, 147.

20 For a recent biography of Kapteyn, see van der Kruit 2015; But see also the essays in van der Kruit and van Berkel 2000.

by a grant from the British Royal Society, David Gill, director of the Royal Observatory at the Cape of Good Hope, aimed to produce a photographic star map of the southern hemisphere. The result was a major collaborative effort between Gill and Kapteyn. Gill and two assistants secured the photographic plates. The plates were then shipped to Groningen for Kapteyn and his assistants to measure them. The resulting catalogue contained the positions and photographic magnitudes of over 450,000 stars. As Lankford has pointed out:

> Kapteyn and Gill were among the first since Bond [at Harvard] to engage in sustained research on such fundamental problems as the determination of photographic magnitudes and the measurement of stellar coordinates on photographic plates, and the [Cape Photographic Durchmusterung] paved the way for the international *Carte du Ciel* project.[21]

But even as late as 1887, such projects were resisted by the practitioners of the older sort of positional astronomy who were afraid that photographic methods would replace meridian instruments and so the Royal Society stopped funding Gill in that year.[22]

Kapteyn later also became the driving force and central figure in the international plan to secure an enormous body of data on stars in a series of 'Selected Areas'. This information would then feed into his pioneering researches on the structure of the galactic system (of which more later). Through these collaborative means, Kapteyn had made himself relevant, indeed a world leader, at Groningen, despite the institutional difficulties. Kapteyn's concern to address a specific problem using a huge collection of data also marks him out as an exemplary practitioner of what we will later term 'Second Stage Astrophysics'.

But how, in 1920, was Pannekoek to make himself relevant at Amsterdam and perform 'cutting-edge' research? Pannekoek also faced a challenge that Kapteyn had not. Whereas Kapteyn in the 1880s and early 1890s did not have to take into account much in the way of competition from the US, American astronomers and telescopes loomed very large by 1910, if not well before.[23] Pannekoek made himself relevant by establishing an Astronomical Laboratory in the manner of Kapteyn, instead of operating an observatory.

21 Lankford 1984, 27.

22 Lankford 1984, 26.

23 For an important discussion of how Swedish astronomers dealt with the issue of making themselves relevant in the face of US telescopes and resources, see Holmberg 1999.

Pannekoek was sufficiently successful that he would win prestigious awards, such as an Honorary Degree from Harvard University in 1936 and the Gold Medal of the Royal Astronomical Society in 1951, widely regarded by astronomers at the time as one of the very top honours in astronomy.

Collaboration and Competition: The Rise of American Astronomy

Over the course of the nineteenth century, big cooperative projects became an increasingly significant feature of astronomy. Many European observatories were engaged in the single largest of them at the end of the nineteenth century, the *Carte du Ciel*, the aim of which was to photograph the entire sky and to produce both a catalogue and chart of the observed stars. The leaders of the project reckoned that over 88,000 photographic plates would have to be taken, measured, and the results compiled. The participating observatories expected to be engaged for twenty years. The Paris Observatory was the headquarters of the project, and twelve other European observatories were involved over its lifetime. The *Carte*, however, had a negative impact on European astronomy as many observatories and astronomers were locked into a costly project of what proved to be very limited scientific worth for many years.[24]

In contrast, no American observatories participated in the *Carte*, and so the expansion and remaking of astronomy in the United States in the late nineteenth and early twentieth centuries were not impeded by the project's hefty demands. And in these years numerous affluent Americans patronized astronomy. Funding arrived in the form of donations or support from philanthropic foundations. The most notable products were the Lick Observatory on Mount Hamilton in California, the Yerkes Observatory of the University of Chicago, and the Carnegie Institution of Washington that from 1904 onwards funded the building and running of what was initially called the Mount Wilson Solar Observatory.[25]

By the time construction started on Mount Wilson, astrophysics had become well established in many countries. It had secured strong institutional support, and its practitioners pursued a range of programmes of research that followed well-defined methods and standards. Following the founding of the Pulkova Observatory in Russia in 1839, positional astronomers, too, had taken it as the model of how things should be done in terms of the scale and efficiency of its

24 Lankford 1997, 394-400; and Lankford 1984. But see also DeVorkin 1998.

25 Miller 1970. On the early history of Lick, see Wright 2003; and on Yerkes, see Osterbrock 1999.

operations.[26] But by the turn of the century, the United States was jockeying with Europe for leadership in observational astrophysics – which was composed principally of the observational study of the spectra of astronomical objects – and Mount Wilson would soon become widely recognized as the premier astrophysical observatory in the world.[27] American observational astronomy was in fact in the process of supplanting Central European astronomy as the world leader.[28] Thus, by the early 1910s, what Lankford has called the 'political economy' of observational astronomy was radically different from that in the early 1880s, and it would be markedly different again by the end of World War I with the financial problems that engulfed Europe.

Third Stage Astrophysics and the Influence of Saha

After he arrived at the University of Amsterdam in 1920, Pannekoek pursued some of his established interests, such as the nature and structure of the Milky Way (as we will see in the next section and in other papers in this volume). But, most importantly, he also struck out in a radically new direction by engaging with and developing the investigations of the Indian theoretical physicist Meghnad Saha. By the early 1920s, astronomers working at numerous observatories had collected a vast body of empirical information on stellar spectra. How, though, were these data to be interpreted and processed? Astronomers like the leading American astrophysicist Henry Norris Russell soon acknowledged that Saha had created the 'master key' to understanding stellar spectra by coupling the Bohr theory of the atom (in which negatively charged electrons orbit in shells around a positively charged nucleus) to thermodynamics.[29] Saha argued that the primary determinant of a star's spectrum is its temperature, with pressure as a secondary factor, and some astronomers, like Russell, now followed Saha's lead and applied atomic physics and quantum mechanics to astrophysics.[30]

Another astronomer to do so was Pannekoek. He had been active in the older sort of astrophysics even in his Leiden years. In 1906, for example, he examined '[t]he relation between the spectra and the colours of the stars'.[31]

26 See, for example, Werrett 2010.
27 van Helden 1984, 138.
28 Among other works that make this point, see Lankford 1997, 371-404; and Baneke 2010, 168.
29 DeVorkin 2000, 178-179.
30 DeVorkin and Kenat 1983a; 1983b. See also Naik 2017.
31 Pannekoek 1906.

But in 1920, he was given copies of a few of Saha's papers and he soon after set about mastering, applying, and extending Saha's findings. Pannekoek published his first paper in this new area in 1922, a study in which he tackled 'ionization in stellar atmospheres'.[32] He contended that:

> Spectral analysis has disclosed the chemical constitution of stellar atmospheres by the lines visible in their spectra. As to their physical state we may infer the temperature from these spectra also, as the series of spectral types, at least from [spectral types B to M] corresponds to a series of decreasing temperatures. But this temperature is not deduced directly from the spectral lines. […] The deduction of the physical conditions in stellar atmospheres from the lines of their spectra has now become possible by the application of the theory of chemical equilibrium on partly ionized gases by Dr MEG NAD SAHA.[33]

For Pannekoek, there was now the exciting prospect that 'a more minute and quantitative investigation of stellar spectra will reveal other characteristics, which in some other way than the state of ionization are connected with diameter, density, temperature, mass and luminosity.'[34] He thereby joined a group of astronomers who had a rigorous training in observational astronomy early in their careers, but who later devoted themselves mainly to interpretation and theoretical researches, with the most prominent other such practitioners being perhaps the British astrophysicist A.S. Eddington and the American Henry Norris Russell. Pannekoek became one of the first practitioners of what I have termed as 'Third Stage Astrophysics' in the tentative periodization of astrophysics given here. Just as Kapteyn, as a practitioner of 'Second Stage Astrophysics', had created and seized opportunities to fashion an Astronomical Laboratory at Groningen, Pannekoek, a practitioner of 'Third Stage Astrophysics', would do the same at Amsterdam, and the output of their respective Astronomical Laboratories exemplified these different stages of astrophysics.

Pannekoek now spent much of his time measuring the relative line intensities in stellar spectra of various spectral types to address issues of spectral classification. For these researches, with no observatory of his own, he measured photographic plates from other observatories,

32 By stellar atmosphere is meant the outer region of a star.

33 Pannekoek 1922, 107; emphasis in the original.

34 Pannekoek 1922, 118.

The Three-Stage Development of Astrophysics

The stages described below are designed to be suggestive rather than definitive. The temporal breaks should not be read as firm as there were very significant periods of overlap. Indeed, there are strong echoes of the 'Great Correlation Era' in evidence today, as DeVorkin has argued. There were very major shifts in each of these stages regarding conceptual tools and technologies. For the first two stages, there were also crucial institutional changes.

1) First Stage Astrophysics; c. 1860-1890. Often pursued by non-professional astronomers with limited formal training, who put the emphasis on the identification and charting of spectral lines. Essentially opportunistic, astrophysicists observed what could be observed, although often with the (usually) distant hope of being able to understand the course of stellar evolution. In this period, some, perhaps many, professional positional astronomers were sceptical about, if not hostile towards, astrophysics. Founding of the first observatories devoted to astrophysics. An exemplar of a practitioner of First Stage Astrophysics: William Huggins.
2) Second Stage Astrophysics; c. 1890-1920. Characterized by a growing number of practitioners and increased professionalization. The researchers' emphasis was on large surveys, collecting spectra and radial velocities of stars, with more emphasis on tackling specific problems rather than merely collecting data. Various attempts were made to correlate different bodies of evidence, with the most significant example being the development of what would be called the Hertzsprung-Russell Diagram. This period also witnessed the formation of the International Union for Cooperation in Solar Research in 1905 (its charge was expanded to include stellar research in 1910), and the establishment of *The Astrophysical Journal* in 1895. In 1921, W. Carl Rufus offered a detailed periodization of American astronomy, and he identified a 'Correlation Period' that began in 1890. DeVorkin has instead termed this era 'The Great Correlation Era'.[1] Exemplars of practitioners of Second Stage Astrophysics: Ejnar Hertszprung and J.C. Kapteyn.
3) Third Stage Astrophysics; c. 1920-1950. In this phase, the field was fully professionalized. The great majority of astronomical observatories were now devoted mostly, if not entirely, to astrophysics. This era saw the introduction into astrophysical practice of state-of-the-art physical theory in terms of the new atomic physics and quantum mechanics, as well as the close combination of theory and observation with a new emphasis on the interpretation of spectral lines. Exemplars of practitioners of Third Stage Astrophysics: Pannekoek and H.N. Russell.

1 Rufus 1921; DeVorkin 2010, 140.

including, for example, the Harvard College Observatory. However, during extended stays at the Bosscha Observatory in Java and the Dominion Astrophysical Observatory in Victoria, Canada as well as on eclipse expeditions, he also secured plates for his own use.[35] Indeed, it is telling of the shifting leadership in observational astronomy, that Kapteyn obtained his plates from Gill at what was effectively a colonial observatory in South Africa, while Pannekoek got the majority of his from institutions in North America.[36] His theoretical researches included, for example, reworking Saha's ionization formula to correct it for departures from thermodynamic equilibrium.[37]

Baneke has argued persuasively that Pannekoek's generation changed Dutch astronomy and 'reorganized the discipline on all levels: research, teaching, institutions, journals, and international contacts. In these few years, they built a modern disciplinary infrastructure that would last until the end of the [twentieth] century.'[38] Here, however, our focus is somewhat different. We have seen that through Pannekoek's move to both interpretive and theoretical astrophysics, and his evident talents in these areas, Pannekoek had, like Kapteyn, effectively solved the problem of how to pursue state-of-the-art research as an astronomer without a telescope. He had done so, moreover, in the face of significant changes in the astronomical enterprise, including its shifting political economy and the rise to preeminence of American observational astronomy.

The Milky Way

Pannekoek, as discussed elsewhere in this volume, was fascinated by the Milky Way from an early age and he was an enthusiastic naked-eye observer as well as a very keen student of photographs of the Milky Way. He was deeply impressed by its complexity throughout his career. His researches on the Milky Way have been very well treated by Tai in this volume and elsewhere, as well as by Tai and van Dongen,[39] so here my focus will be on how he became an early advocate of Harlow Shapley's radical new picture of the stellar system, first advanced publicly in 1918.

35 See, for example, Pannekoek 1927.

36 I am grateful to Chaokang Tai for pointing this out to me.

37 Pannekoek 1926.

38 David Baneke, 'Pannekoek's One Revolution', in this volume, 87-108.

39 Tai and van Dongen 2016; Tai 2017; and his 'The Milky Way as Optical Phenomenon', in this volume, 219-247.

Shapley, an astronomer at the Mount Wilson Observatory in California, argued for what became known as the Big Galaxy. Other astronomers placed the Sun close to the centre of our stellar system. For Shapley, it was tens of thousands of light years distant. Shapley, moreover, reckoned the Big Galaxy to be about 300,000 light years in diameter, and so roughly ten times larger than the usually accepted size. In supporting Shapley's radical, and initially often criticized scheme, Pannekoek again put himself into what turned out to be the vanguard of astronomy.

Towards the end of the nineteenth century and in the early years of the twentieth, more professional astronomers turned their attention to galactic structure and the Milky Way.[40] Three changes were crucial for this shift: advances in photography, the growing number of professional astronomers who tackled problems other than those related to positional astronomy and the forging of powerful new mathematical techniques by a small number of astronomers in pursuit of a plausible model of the Galaxy.

Cornelis Easton, a Dutch popularizer of astronomy and a prominent amateur astronomer in his own right, was among those who at the end of the nineteenth century stressed the observational complexities of the stellar system. He sought to connect the overall structure of the Milky Way with the observed fluctuations in the intensity of its light when he observed in different directions, and in so doing argued for a spiral form for the Galaxy. In 1900, for example, Easton presented 'A New Theory of the Milky Way', in the prestigious American-based *Astrophysical Journal* and sketched the Milky Way as a spiral. But when Easton again argued for a spiral structure for the Milky Way in 1913, he not only presented a revised sketch of the Milky Way, but also drew on photographs of the Milky Way.[41]

Around the turn of the twentieth century, a small number of mathematicians and professional astronomers turned to developing models of the galactic system. Among these were a few who employed sophisticated mathematics and emphasized a consistent mathematical account to fashion different versions of the so-called ellipsoidal model. The ellipsoid model came with varying degrees of empirical input. C.V.L. Charlier, at Lund, and Hugo von Seeliger, at Munich, were two of the three chief exponents in the early twentieth century of what Pannekoek would term 'statistical astronomy' in his *A History of Astronomy*.[42]

40 For background on this section, see Smith 2006; and Paul 1993.

41 Easton 1900; and 1913.

42 Pannekoek 1989, 473.

The Dutch astronomer J.C. Kapteyn was recognized as the leading practitioner of statistical astronomy. As we noted earlier, through his skills, drive, and wide range of contacts and collaborators outside the Netherlands, he became an internationally renowned astronomer. He was also, as I have argued elsewhere, 'an astronomer with a grand passion: the solution of the Sidereal Problem',[43] that is, the solution of the problem of 'the present positions and motions of the stars as a stage in the history of a dynamical system (whether in a steady state or not) and the deduction of the presumable history of the system in the past and in the future'.[44] The Astronomical Laboratory at Groningen was designed to allow Kapteyn to tackle the Sidereal Problem.

Kapteyn showed himself to be a new sort of astrophysicist, a practitioner of what we termed earlier as 'Second Stage Astrophysics'. He was not interested in surveys for the sake of surveys or piling-up information for no clear end purpose, in the manner typical of many first-generation astrophysicists. Rather, he sought great masses of accurate data to solve a very major problem. Kapteyn had, therefore, 'married the concern for the diversity of stars, which was so important to astrophysicists, to the traditional values of mathematical astronomers of exactness and rigorous mathematics'.[45] In so doing, Kapteyn had a great influence on Dutch astronomy and astronomers. 'Kapteyn', as Sullivan has argued, 'found a niche. [...] Dutch astronomers were masters at this type of analysis.'[46] In Sullivan's view, this sort of research was marked by 'thoroughness, neatness, and precision' and the avoidance of speculation.[47]

Despite his careful approach and concern for errors, Kapteyn's quest to solve 'The Sidereal Problem' ended in a grand failure. Within a decade of Kapteyn's death in 1922, astronomers were agreed that the obscuring matter spread throughout galactic space undermined the reliability of his star-counts and so the distances he derived for distant stars close to the galactic plane.[48] Kapteyn had, of course, been fully aware of the potential seriousness of interstellar absorption for his investigations. He had returned to the question of its existence and nature at various times. Towards the end of his career, however, Kapteyn had been persuaded by Shapley's researches of the colours of stars in remote globular clusters that the effects of a general interstellar absorption are relatively minor. If so, it would have relatively little effect on

43 Smith 2000, 183.

44 Russell 1919, 391. For the context of this paper by Russell, see DeVorkin 2000, 138-152.

45 Smith 2000, 190.

46 Sullivan 2000, 236.

47 Sullivan 2000, 237.

48 van der Kruit 2015; see also Smith 2000, 188.

his derived distances.[49] At the core of Shapley's studies of globular clusters were his estimates of the distances of various sorts of stars within them, and these distances led him to a new and radical view of the stellar system. In early 1918, Shapley told the leading British astrophysicist A.S. Eddington that his determination of the distances to all the known globular clusters had very rapidly settled the 'whole sidereal structure'. The globular clusters, he argued, surrounded and framed the stellar system.[50] Soon after, Shapley was explaining to the Director of the Mount Wilson Observatory that the Galaxy is in effect a collection of star clusters and far bigger than astronomers had believed, some 300,000 light years or so in diameter. The Sun, furthermore, is several tens of thousands of light years away from the centre.[51] Here was a very different picture from the others astronomers discussed in the late 1910s, which always contained a relatively central Sun and which often portrayed the galactic system as lens-shaped and perhaps 30,000 light-years across.

It is misleading, however, to regard the systems of Kapteyn and Shapley as entirely opposed to one another and to assume that astronomers plumped for either Kapteyn's system or Shapley's.[52] As Gingerich remarks, as 'for the divergence between Kapteyn's heliocentric cosmos and Shapley's much vaster galactocentric system, the differences are much more stark in the modern telling than in the historical actuality around 1920.'[53] Both Kapteyn's version of the stellar system and Shapley's Big Galaxy thesis, for example, were larger than the sizes typically quoted (by factors of two and ten). But there were nevertheless major differences in the approach and results that underpinned the two systems. Most significantly, Kapteyn and the statistical astronomers worked outwards from our stellar neighbourhood. Shaply, on the other hand, worked inwards from the Galaxy's outer regions as defined by the globular clusters.[54] Kapteyn's model was well regarded by some astronomers, while many were reluctant, initially at least, to accept Shapley's system as credible. The best known such critic was the Lick Observatory astronomer H.D. Curtis who deployed a range of objections to Shapley's scheme in the so-called Great Debate of April 1920.[55] Pannekoek, however, was one of Shapley's earliest public supporters.

49 Smith 2000, 188; 1982, 57-59; and Paul 1993, 101-106.

50 H. Shapley to A.S. Eddington, 8 January 1918, HS; and Smith 1982, 61.

51 H. Shapley to G.E. Hale, 19 January 1918, HS.

52 Smith 1982, 69.

53 Gingerich 2000, 191.

54 Smith 1982, 68.

55 Hoskin 1976; and Smith 1982, 77-87. Curtis also held strong doubts about Kapteyn's results: Smith 1982, 85.

Pannekoek had already concluded in 1910 that Kapteyn's mathematical approach and assumptions meant an overall, symmetrical ellipsoid shape for the galactic system in which the stars slowly decrease in number as one travels further from the solar neighbourhood. As Tai and van Dongen have argued, Pannekoek instead contended 'that the visual appearance of the Milky Way, with its patchy light structure, completely contradicted such a symmetry. His solution was to focus on specific features of the Milky Way that stood out visually and determine the star distribution function for each of these features individually, while still using Kapteyn's numerical methods.'[56] In examining star clouds in the directions of the constellations of Aquila and Cygnus, Pannekoek decided that instead of a gradual thinning out of stars, there was an increasing number of the fainter stars, thereby contradicting what could be expected from the ellipsoid model.

Pannekoek again emphasized clusters of stars in a paper published in 1919. He noted that the underlying procedure adopted by statistical astronomers was to develop formulae to 'define our star system as a figure of revolution, in which the star density depends on distance and galactic latitude.' Employing this approach, the Sun was represented 'as lying in the midst of a flat star cluster whose densest parts measure some 1000 parsecs.' But Pannekoek, who of course had spent very many hours from his youth studying the intricacies of the Milky Way, emphasized that

> [such a model] is not in accordance [...] with the appearance of the Galaxy. We see the appearance of the Milky Way as a belt of luminous clouds, patches, and drifts, divided by less luminous regions or dark gaps and rifts. If we go in the direction of such a star-cloud, the star-density, after we have left our central cluster, must increase at first on the nearer side of the centre of the cloud, and decrease on the further wide. The aspect of the Milky Way shows that by treating the galactic zone as a whole we intermingle parts of the universe of a great diversity of structure, viz. the aggregation of stars in clouds, separated by regions agreeing perhaps with the galactic poles. In studying the distribution of stars in our universe we must treat the different parts of the Galaxy, especially the great star-clouds and streams, separately.[57]

Pannekoek indeed treated each of the different parts of the Galaxy separately to derive the changes in star density with distance. By this route, he ended-up

56 Tai and van Dongen 2016, 63.

57 Pannekoek 1919, 500.

siding with Shapley. Some of the bright parts of the Milky Way, Pannekoek calculated, were some 40,000 to 60,000 parsecs distant, and 'the starry masses of the Galaxy are spread over space as far as the remotest [globular] clusters, and clearly both belong to one system.' Although Shapley's arguments in favour of an eccentric position of the Sun in the galactic system were, 'contrary to the common view', Pannekoek reckoned that 'Shapley's result is wholly in accordance with the aspect of the Milky Way.'[58]

Shapley, moreover, had not merely expanded the size of the stellar system and placed the Sun in an eccentric position. He had also advanced a dynamic picture of the collection of globular clusters and the Galaxy (what he referred to as a super-system), and Pannekoek looked favourably on this picture too. For Shapley:

> [The] flat form and heterogeneity [of the galactic system], its content of numerous fragmentary systems (open [star] clusters, wide binaries, spectrally-similar groups) of apparently different ages and separate origins, and its control over the motions of the clusters and near-by spirals, have led me for some years to advocate the hypothesis that the Galaxy is a growing composite of disintegrating minor systems.[59]

The globular clusters swing to and fro through the star clouds of the galactic system and on every passage their form changes and their speed is reduced. Over time, the globular clusters are diverted into the galactic regions and 'gradually robbed of their stars' so that they are converted into open star clusters.[60] Globular clusters had not been sighted close to the galactic plane, Shapley pointed out. Maybe the very limited time they spent traversing the galactic plane was the reason.

Shapley's vision of the Galaxy as a growing collection of star clusters was a congenial one for Pannekoek even though it was hardly a well worked-out mathematical model. In what for Pannekoek was a rare moment of speculation, he agreed that perhaps when the globular clusters come from the 'void space into the star-filled galactic regions, [they] are gradually broken up and dispersed into open clusters by the attraction of these stars.'[61] For once,

58 Pannekoek 1919, 507.

59 Shapley 1923, 316. Note that, at the time, Shapley did not believe that spirals were distant galaxies.

60 Shapley 1923, 319.

61 Pannekoek 1919, 500. Pannekoek also noted that Shapley had raised the possibility that the absence of globular clusters from the galactic plane might be explained by the presence of obstructing dark nebulae blocking the view of low-lying globular clusters.

Pannekoek, whose scientific approach can be described as that of a 'close empiricist' very much in the manner of the Dutch school as discussed by Sullivan, agreed with what was an example on Shapley's part of imagination and speculative reasoning.[62]

Other Dutch and Netherlands-based astronomers beside Pannekoek in time also swung behind Shapley's scheme. In May 1922, Shapley met in Leiden with Ejnar Hertzsprung, Pannekoek, and two of Kapteyn's students, including W.J.A. Schouten, who in 1919 had argued that Shaply had overestimated the distances to the globular clusters by a factor of around eight. Shapley, they all decided, was basically correct.[63] Pieter J. van Rhijn, who was a PhD student of Kapteyn's as well as a collaborator of his and his successor at Groningen, however, stuck to his guns. He co-authored 'On the distribution of the stars in space especially at high galactic latitudes' with Kapteyn in 1920, in which they advocated an ellipsoid model for the galactic system. The two of them also argued in 1922 that Shapley had misused the Cepheid variable stars as his main distance indicators and that his distances to them were in fact seven times too big.[64] If that were so, then Shapley's Big Galaxy would have to be shrunk.

In 1922, Kapteyn in some respects pulled together the results of his life's work on the sidereal problem in a paper published in *Astrophysical Journal.* He again argued for an ellipsoid model and concluded that the Sun is close to the centre of the Galaxy, and that the galactic system extends for about 8500 parsecs along the galactic plane and at 1700 parsecs at right angles to the plane before the star density reaches one hundredth of the density in the neighbourhood of the Sun. Even here, after decades of effort to solve the Sidereal Problem Kapteyn still wrote of a 'First attempt at a theory of the arrangement and motion of the sidereal system.'[65]

In 1924, Pannekoek returned to the problem of the distribution of stars within the Galaxy to search for star clusters that, when their light was aggregated, could explain the appearance of the Milky Way. For Pannekoek, the galactic system was to be understood as an accumulation of loose clusters, and so was in line with Shapley's picture, but very different from Kapteyn's ellipsoid.[66]

62 The place of imagination and speculative reasoning in nineteenth-century science has been examined by, among others, Willis 2011. With Shapley's 'Big Galaxy' we see imagination and speculative reasoning in early twentieth-century astronomy.

63 Paul 1981; and van der Kruit 2015, 593. On Schouten's 1919 study, see also Smith 1982, 69.

64 Kapteyn and Rhijn 1922.

65 Kapteyn 1922.

66 Pannekoek 1924. For a commentary on this paper, see Tai and van Dongen 2016, 63-64; and Tai 2017, 242-245.

By the early 1930s, the generally accepted picture of the galactic system was quite different from those in play in the late 1910s and early 1920s. Researches in the second half of the 1920s of a possible galactic rotation, including most importantly by the Swedish astronomer Bertil Lindblad and Dutch astronomer Jan Oort, persuaded astronomers that the galactic system rotates and that the direction of the system's centre is in agreement with the centre of the system of globular clusters as identified by Shapley. Oort placed the centre of the galactic system around 6000 parsecs away, significantly smaller than Shapley's estimate. This difference, most astronomers soon decided in the early 1930s, could be readily explained by the fact that Shapley had taken no account of interstellar absorption in his distance determinations. In 1930, the Lick Observatory astronomer Robert Trumpler advanced arguments in favour of a significant interstellar absorption that other astronomers found convincing.[67] The upshot was that Shapley had overestimated his distances. The Big Galaxy was not as big as he had initially calculated; it needed to be shrunk by about a factor of three. The discrepancy between Oort's and Shapley's estimate of the distance to the centre of the Galaxy now largely disappeared.[68]

In 1932, in his semi-popular book *Kosmos*, Willem de Sitter displayed a diagram of the galactic system provided by Oort. It showed a system with a diameter of around 35,000 parsecs surrounded by globular clusters.[69] This image was strikingly different from those offered by Kapteyn in his two major papers of 1920 and 1922 that, because of his death in 1922, ended his life's work on the sidereal problem. Instead, Kapteyn's model formed just one part of Oort's version of the stellar system.

By the early 1930s and the publication of *Kosmos*, Kapteyn's model was generally reckoned by astronomers to be badly outdated. As Pannekoek put it in his *A History of Astronomy*: 'The main features of the stellar system to which our Sun belongs, its shape and its state of motion, are now established as far different from what had been found in Kapteyn's pioneering investigations.'[70]

The year of the original Dutch publication of Pannekoek's history of astronomy, 1951, was also the year that William W. Morgan, an astronomer at the Yerkes Observatory, and his collaborators provided what astronomers generally agreed was persuasive evidence that the Galaxy has a spiral

67 Trumpler 1930. See also Seeley 1973.

68 Smith 2006, 329.

69 W. de Sitter 1932.

70 Pannekoek 1989, 482.

structure. Numerous astronomers had advocated a spiral structure since the middle of the nineteenth century, including, as we have noted, Cornelis Easton. But it was Morgan's study of the distances to H II regions and bright O and B stars within them that astronomers regarded as decisive and earned him an ovation when he presented a paper on his results at a meeting of the American Astronomical Society in 1951.[71]

At the same meeting, Oort delivered an invited lecture on the 'Problems of Galactic Structure'. Here, he gave a breakdown of what he regarded as the three key phases of the developments in knowledge of the galactic system. The first had been initiated by Kapteyn's researches, though he 'did *not* reach the principal aim he had set out for, because of the unexpected strength of interstellar absorption near the galactic plane.' Shapley had begun the second great development with his investigations of the arrangement of the globular clusters. 'It seems that at present', Oort argued, 'a third phase in the development of galactic research has begun by the successful reception of radiation at radio frequencies. This research is still in its early infancy.'[72] In hindsight, we can now see that Oort was surely correct. The study of galactic structure at radio wavelengths, in which Dutch astronomers were very much in the forefront, *did* open up extremely important new research avenues.[73] But the start of observations of the Milky Way in other wavelength ranges, especially in the infrared, would of course later prove to be crucial additions to the optical and radio. As Pannekoek argued from the vantage point of 1951:

> The establishment of the galactic system is not the end, but rather a beginning of research, specifying a task. Just as many centuries were needed after the establishment of the solar system for the investigation of its contents, structure, and details, its laws and characteristics, so it is now with the stellar system.[74]

Conclusions

J.C. Kapteyn was the leading Dutch astronomer of the late nineteenth and early twentieth century. When he assumed the professorship of astronomy and theoretical mechanics at Groningen in 1878, many astronomers were

71 Gingerich 1985; and Smith 2006, 331.
72 Oort 1952, 233; emphasis in the original.
73 On the early development of radio astronomy, see Sullivan 2009.
74 Pannekoek 1989, 482.

sceptical of, and some actively hostile towards, astrophysics. But Kapteyn pressed on and in the end helped to establish a new sort of astrophysics, what we described earlier as 'Second Stage Astrophysics', in which he sought to take full account of the range of different sorts of stars as well as analyse rigorously their properties. He had done so despite a lack of resources at Groningen, and had thereby provided one answer to the question of how to be an effective astronomer without a telescope.

Kapteyn died in 1922. By this time, we have seen that a new sort of astrophysics had started to emerge, one that had been given its initial impetus by the researches of Meghnad Saha. We termed this 'Third Stage Astrophysics'. Pannekoek effectively solved the problem of how to be relevant and perform 'competitive' research at the University of Amsterdam despite his lack of resources, including the complete lack of telescopes and an observatory, and in the face of the rise of American astronomy, by rapidly grasping the importance of Saha's path-breaking researches and both developing and applying to actual stars this novel sort of astrophysics. Pannekoek's initial expertise had been in positional astronomy, but he became one of the earliest practitioners of 'Third Stage Astrophysics'.

Pannekoek also positioned himself as a modern astronomer by quickly realizing the importance of Shapley's new picture of the stellar system, advanced publicly in 1918. The next year, Pannekoek became one of the first astronomers to publish additional evidence in support of Shapley, and in so doing underlined the severe limitations of the models developed by the statistical astronomers, including Kapteyn. Pannekoek the astronomer, then, was both very much of, as well as a maker of, his time.

Archives

HS Papers of Harlow Shapley, 1906-1966, HUG 4773. Harvard University Archives.

Bibliography

Baneke, David. 2005. '"Als bij toverslag". De renovatie en nieuwe bloei van de Leidse Sterrewacht 1918-1924'. *BMGN – Low Countries Historical Review* 120(2): 207-225.

—. 2010. 'Teach and Travel: Leiden Observatory and the Renaissance of Dutch Astronomy in the Interwar Years'. *Journal for the History of Astronomy* 41(2): 167-198.

—. 2015. *De ontdekkers van de hemel. De Nederlandse sterrenkunde in de twintigste eeuw*. Amsterdam: Prometheus Bert Bakker.

Becker, Barbara J. 2011. *Unravelling Starlight: William and Margaret Huggins and the Rise of the New Astronomy*. Cambridge: Cambridge University Press.

Clerke, Agnes Mary. 1885. *A Popular History of Astronomy during the Nineteenth Century*. Edinburgh: Adam & Charles Black.

DeVorkin, David H. 1998. 'The American Astronomical Community'. Review of *American Astronomy: Community, Careers, and Power, 1859-1940*, by John Lankford. *Journal for the History of Astronomy* 29(4): 389-392.

—. 2000. *Henry Norris Russell: Dean of American Astronomers*. Princeton, NJ: Princeton University Press.

—. 2010. 'Extraordinary Claims Require Extraordinary Evidence: C.H. Payne H.N. Russell and Standards of Evidence in Early Quantitative Spectroscopy'. *Journal of Astronomical History and Heritage* 13(2): 139-144.

DeVorkin, David H., and Ralph Kenat. 1983a. 'Quantum Physics and the Stars I: The Establishment of a Stellar Temperature Scale'. *Journal for the History of Astronomy* 14(2): 102-132.

—. 1983b. 'Quantum Physics and the Stars II: Henry Norris Russell and the Abundances of the Elements in the Atmospheres of the Sun and Stars'. *Journal for the History of Astronomy* 14(3): 180-222.

Dewhirst, David W. 1985. 'Meridian Astronomy in the Private and University Observatories of the United Kingdom: Rise and Fall'. *Vistas in Astronomy* 28(1): 147-158.

Donnelly, Kevin. 2014. 'On the Boredom of Science: Positional Astronomy in the Nineteenth Century'. *British Journal for the History of Science* 47(3): 479-503.

Easton, Cornelis. 1900. 'A New Theory of the Milky Way'. *Astrophysical Journal* 12(2): 136-158.

—. 1913. 'A Photographic Chart of the Milky Way and the Spiral Structure of the Galaxy'. *Astrophysical Journal* 37(2): 105-118.

Gingerich, Owen. 1985. 'The Discovery of the Spiral Arms of the Milky Way'. In *The Milky Way Galaxy: Proceedings of the 106th Symposium, Groningen, Netherlands, May 30-June 3, 1983*, ed. by Hugo van Woerden, Ronald J. Allen, and W. Butler Burton. Dordrecht: D. Reidel, 59-70.

—. 2000. 'Kapteyn, Shapley, and Their Universes'. In *The Legacy of J.C. Kapteyn: Studies on Kapteyn and the Development of Modern Astronomy*, ed. by Pieter C. van der Kruit and Klaas van Berkel. Dordrecht: Kluwer, 191-212.

Helden, Albert van. 1984. 'Building Large Telescopes, 1900-1950'. In *The General History of Astronomy, Volume 4: Astrophysics and Twentieth-Century Astronomy to 1950: Part A*, ed. by Owen Gingerich. Cambridge: Cambridge University Press, 134-152.

Hentschel, Klaus. 2002. *Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching*. Oxford: Oxford University Press.

Herrmann, Dieter B. 1975. 'Zur Vorgeschichte des Astrophysikalischen Observatorium Potsdam (1865 bis 1874)'. *Astronomische Nachrichten* 296(6): 245-259.

Holmberg, Gustav. 1999. *Reaching for the Stars: Studies in the History of Swedish Stellar and Nebular Astronomy, 1860-1940*. Lund: Lund University.

Hoskin, Michael. 1976. 'The "Great Debate": What Really Happened'. *Journal for the History of Astronomy* 7(3): 169-182.

Hufbauer, Karl. 1993. *Exploring the Sun: Solar Science since Galileo*. Baltimore: Johns Hopkins University Press.

Kapteyn, Jacobus C. 1922. 'First Attempt at a Theory of the Arrangement and Motion of the Sidereal System'. *Astrophysical Journal* 55(4): 302-328.

Kapteyn, Jacobus C., and Pieter J. Rhijn. 1922. 'The Proper Motions of δ-Cephei Stars and the Distances of the Globular Clusters'. *Bulletin of the Astronomical Institutes of the Netherlands* 1(8): 37-42.

Kruit, Pieter C. van der. 2015. *Jacobus Cornelius Kapteyn: Born Investigator of the Heavens*. Cham: Springer.

Kruit, Pieter C. van der, and Klaas van Berkel, eds. 2000. *The Legacy of J.C. Kapteyn: Studies on Kapteyn and the Development of Modern Astronomy*. Dordrecht: Kluwer.

Lankford, John. 1984. 'The Impact of Photography on Astronomy'. In *The General History of Astronomy: Volume 4, Astrophysics and Twentieth-Century Astronomy to 1950: Part A*, ed. by Owen Gingerich. Cambridge: Cambridge University Press, 16-39.

—. 1997. *American Astronomy: Community, Careers, and Power, 1859-1940*. Chicago: University of Chicago Press.

Laurie, Philip S., Jacques Lévy, Aleksandr A. Mikhailov, Howard Plotkin, Deborah Warner, Trudy E. Bell, and Dieter B. Herrmann. 1984. 'Astronomical Institutions'. In *The General History of Astronomy: Volume 4, Astrophysics and Twentieth-Century Astronomy to 1950: Part A*, ed. by Owen Gingerich. Cambridge: Cambridge University Press.

Meadows, Arthur Jack. 1973. *Science and Controversy. A Biography of Sir Norman Locky*. Cambridge, MA: MIT Press.

—. 1984a. 'The New Astronomy'. In *The General History of Astronomy: Volume 4, Astrophysics and Twentieth-Century Astronomy to 1950: Part A*, ed. by Owen Gingerich. Cambridge: Cambridge University Press, 59-72.

—. 1984b. 'The Origins of Astrophysics'. In *The General History of Astronomy: Volume 4, Astrophysics and Twentieth-Century Astronomy to 1950: Part A*, ed. by Owen Gingerich. Cambridge: Cambridge University Press, 3-15.

Miller, Howard S. 1970. *Dollars For Research: Science and Its Patrons in Nineteenth Century America*. Seattle: University of Washington Press.

Naik, Pramod V. 2017. *Meghnad Saha, His Life in Science and Politics*. Cham: Springer.

Narrien, John. 1833. *An Historical Account of the Origin and Progress of Astronomy*. London: Baldwin & Cradock.

Oort, Jan H. 1952. 'Problems of Galactic Structure'. *Astrophysical Journal* 116(2): 233-250.

Osterbrock, Donald E. 1999. *Yerkes Observatory, 1892-1950: The Birth, Near Death, and Resurrection of a Scientific Research Institution*. Chicago, IL: University of Chicago Press.

Pannekoek, Anton. 1906. 'The Relation between the Spectra and the Colours of the Stars'. *Proceedings of the Section of Sciences, Koninklijke Akademie van Wetenschappen te Amsterdam* 9(1): 292-302.

—. 1919. 'The Distance of the Milky Way'. *Monthly Notices of the Royal Astronomical Society* 79(7): 500-507.

—. 1922. 'Ionization in Stellar Atmospheres'. *Bulletin of the Astronomical Institutes of the Netherlands* 1(19): 107-118.

—. 1924. *Researches on the Structure of the Universe 1. The Local Star System Deduced from the Durchmusterung Catalogues*. Publications of the Astronomical Institute of the University of Amsterdam 1. Amsterdam: Stadsdrukkerij.

—. 1926. 'The Ionization Formula for Atmospheres Not in Thermodynamic Equilibrium'. *Bulletin of the Astronomical Institutes of the Netherlands* 3(110): 207-209.

—. 1927. 'The Determination of Absolute Line Intensities in Stellar Spectra'. *Bulletin of the Astronomical Institutes of the Netherlands* 4(121): 1-6.

—. 1989. *A History of Astronomy*. New York: Dover.

Paul, E. Robert. 1981. 'The Death of a Research Program: Kapteyn and the Dutch Astronomical Community'. *Journal for the History of Astronomy* 12(2): 77-94.

—. 1993. *The Milky Way Galaxy and Statistical Cosmology, 1890-1924*. Cambridge: Cambridge University Press.

Pyenson, Lewis. 1989. *Empire of Reason: Exact Sciences in Indonesia, 1840-1940*. Leiden: Brill.

Rothenberg, Marc. 1974. 'The Educational and Intellectual Background of American Astronomers, 1825-1875'. PhD Thesis, Bryn Mawr, PA: Bryn Mawr College.

Rue, Warren de la. 1861. 'Proceedings of the Chemical Society'. *Chemical News* 4(92): 130-133.

Rufus, W. Carl. 1921. 'Proposed Periods in the History of Astronomy in America'. *Popular Astronomy* 29(288): 393-404, 468-475.

Russell, Henry Norris. 1919. 'Some Problems of Sidereal Astronomy'. *Proceedings of the National Academy of Science* 5(10): 391-416.

Schaffer, Simon. 1988. 'Astronomers Mark Time: Discipline and the Personal Equation'. *Science in Context* 2(1): 115-145.

Seeley, Daniel H. 1973. 'The Development of Research on the Interstellar Medium c. 1900-1940: Diffuse Nebulae, Interstellar Gas, and Interstellar Extinction'. PhD Thesis, Boston: Boston University.

Shapley, Harlow. 1923. 'The Galactic System'. *Popular Astronomy* 31(305): 316-327.

Sitter, Willem de. 1932. *Kosmos: Course of Six Lectures on the Development of Our Insight into the Structure of the Universe, Delivered for the Lowell Institute in Boston, in November 1931*. Cambridge, MA: Harvard University Press.

Sitter, Wolter Reinhold de. 2000. 'Kapteyn and de Sitter: A Rare and Special Teacher-Student and Coach-Player Relationship'. In *The Legacy of J.C. Kapteyn: Studies on Kapteyn and the Development of Modern Astronomy*, ed. by Pieter C. van der Kruit and Klaas van Berkel. Dordrecht: Kluwer.

Smith, Robert W. 1982. *The Expanding Universe: Astronomy's 'Great Debate,' 1900-1931*. Cambridge: Cambridge University Press.

—. 2000. 'Kapteyn and Cosmology'. In *The Legacy of J.C. Kapteyn: Studies on Kapteyn and the Development of Modern Astronomy*, ed. by Pieter C. van der Kruit and Klaas van Berkel. Dordrecht: Kluwer, 175-190.

—. 2003. 'The Remaking of Astronomy'. In *Cambridge History of Science, Volume 5: Modern Physical and Mathematical Science*, ed. by Mary Jo Nye. Cambridge: Cambridge University Press.

—. 2006. 'Beyond the Big Galaxy: The Structure of the Stellar System 1900-1952'. *Journal for the History of Astronomy* 37(3): 307-342.

Struve, Otto. 1943. 'Fifty Years of Progress in Astronomy'. *Popular Astronomy* 51(509): 469-481.

Sullivan, Woodruff T., III. 2000. 'Kapteyn's Influence on the Style and Content of Twentieth Century Dutch Astronomy'. In *The Legacy of J.C. Kapteyn: Studies on Kapteyn and the Development of Modern Astronomy*, ed. by Pieter C. van der Kruit and Klaas van Berkel. Dordrecht: Kluwer.

—. 2009. *Cosmic Noise: A History of Early Radio Astronomy*. Cambridge: Cambridge University Press.

Tai, Chaokang. 2017. 'Left Radicalism and the Milky Way: Connecting the Scientific and Socialist Virtues of Anton Pannekoek'. *Historical Studies in the Natural Sciences* 47(2): 200-254.

Tai, Chaokang, and Jeroen van Dongen. 2016. 'Anton Pannekoek's Epistemic Virtues in Astronomy and Socialism: Personae and the Practice of Science'. *BMGN – Low Countries Historical Review* 131(4): 55-70.

Trumpler, Robert J. 1930. 'Preliminary Results on the Distances, Dimensions and Space Distribution of Open Star Clusters'. *Lick Observatory Bulletin* 14(420): 154-188.

Werrett, Simon. 2010. 'The Astronomical Capital of the World: Pulkovo Observatory in the Russia of Tsar Nicholas I'. In *The Heavens on Earth: Observatories and Astronomy in Nineteenth-Century Science and Culture*, ed. by David Aubin, Charlotte Bigg, and Heinz Otto Sibum. Durham, NC: Duke University Press.

Whewell, William. 1833. 'Address to the British Association for the Advancement of Science'. In *Report of the Third Meeting of the British Association for the*

Advancement of Science; Held at Cambridge. London: British Association for the Advancement of Science, xi-xxxii.

Willis, Martin. 2011. *Vision, Science and Literature, 1870-1920: Ocular Horizons*. London: Pickering & Chatto.

Wright, Helen. 2003. *James Lick's Monument: The Saga of Captain Richard Floyd and the Building of the Lick Observatory*. Cambridge: Cambridge University Press.

About the Author

Robert W. Smith is Professor of History in the Department of History and Classics at the University of Alberta. He has written extensively on the history of nineteenth- and twentieth-century astronomy, and his books include *The Expanding Universe: Astronomy's 'Great Debate' 1900-1931*, *The Space Telescope: A Study of NASA, Science, Technology, and Politics*, and *Hubble Cosmos*. He has been a Fellow of the National Humanities Center and in 2007 was the Lindbergh Chair of Aerospace History at the Smithsonian Institution's National Air and Space Museum.