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SPECTROSCOPY—SO WHAT?

Matthew Stanley
Gallatin School of Individualized Study, New York University,
1 Washington Place, New York, NY 10003, USA.
E-mail: matt.stanley@nyu.edu

Abstract: The development of astronomical spectroscopy allowed amazing achievements in investigating the composition and motion of celestial bodies. But even beyond specific measurements and results, the fruitfulness and practice of spectroscopy had important ramifications on a more abstract level. This paper will discuss ways in which spectroscopy inspired or boosted new theories of the atom, life, and the Universe; redrew the boundaries among scientific disciplines; demonstrated the unity of terrestrial and celestial physical laws; changed what counted as scientific knowledge; and even revealed divine mysteries. Scientists and science writers from the first half-century of astronomical spectroscopy will be discussed, including James Clerk Maxwell, William Crookes, John Tyndall, Agnes Clerke, William Huggins and Norman Lockyer.

Keywords: spectroscopy, history of astronomy

1 INTRODUCTION

Science is not driven by facts alone. When a new method such as astronomical spectroscopy is developed, it is tempting to look back and celebrate the new facts generated by the technique. But science is also driven by larger concerns and issues, and most major breakthroughs contribute to these larger concerns as much as they unravel specific technical puzzles. Thus we might ask: 'Spectroscopy? So what?' Why did scientists care about this new technique? How did it change the way they worked, and the way they thought about themselves and the Universe?

Thinking along these lines, the Victorians were stunned by Kirchhoff and Bunsen's achievement. There was widespread astonishment at what could be done with the spectroscope (Schuster, 1881). One commentator described the psychic impact of the discovery:

> In no science, perhaps, does the sober statement of the results which have been achieved appeal so strongly to the imagination and make so evident the almost boundless powers of the mind of man … [Spectroscopy] is worthy to be regarded as the scientific epic of the century. (Watts, 1904: v-vi).

The ability to peer inside incredibly distant bodies was something of a shock. What had been restricted to the laboratory and the workshop now extended across the Universe "… into almost unlimited space …" (Roscoe, 1873: 2). As Norman Lockyer (1873: 107) put it, "… we can take the very Sun itself to pieces." (cited by Schaffer, 1995: 283). These remarkable explorations came to be known as the 'New Astronomy'.

Part of the excitement about these techniques was that they seemed to do what had been forbidden explicitly by Auguste Comte, the widely-influential philosopher of science (see Hearnshaw, 2010) who in the 1830s notoriously declared that the composition of a star would be forever unattainable by science and indeed was the perfect example of unscientific knowledge (Comte, 2004: 130). But after 1859, it seemed that astronomers had dramatically shattered those philosophical boundaries:

> Before the discoveries of Bunsen and Kirchhoff no philosopher had ever ventured to think it possible that we should be able to analyse the sun and stars. (Watts, 1904: v).

Distance no longer seemed to matter, truly opening up the entire Universe to scientific investigation:

> The interest which the new discovery created in scientific and unscientific circles was due to the apparent victory over space which it implied. No matter whether a body was placed in our laboratory or a thousand miles away—at the distance of the sun or of the farthest star. (Schuster, 1881: 468).

This remarkable expansion of scientific possibility allowed spectroscopy to speak to a number of the most important debates of the century. These could easily fill a book, but here I will address three broad topics: the unity of natural laws and matter; the existence and structure of atoms; and the meaning of the Universe.

2 THE UNITY OF LAWS AND MATTER

A concern going back centuries regarded the question of whether the laws of nature that we can observe and experiment with here on Earth apply to the Universe as a whole. While the universality of laws is widely accepted in the twenty-first century, it was not always obvious that this is the case—the Aristotelian Universe rejected it completely. This principle of the unity of natural laws formed an important part of Newton's 'rules of reasoning' and was one of the major methodological contributions of his work (see Cohen, 1995: 116-118).

Unity became axiomatic for scientists, but it was difficult to know whether it was actually true. By the middle of the nineteenth century, the only law that astronomers were assured reached beyond our Solar System was that of Newtonian gravity—thanks to William Herschel's careful observations of double stars (Huggins and Miller, 1864). Spectrum analysis dramatically changed this by extending the laws of light, heat, and chemistry everywhere a telescope could be pointed (ibid.). Recognizable spectral lines linked our laboratories with the rest of the Universe (e.g. see Pasachoff and Suer, 2010).

Agnes Clerke (Figure 1), one of the great science writers of the nineteenth century, noted that this seemed to complete 'the unification of the cosmos' started by Newton:

> It means the establishment of a science of Nature whose conclusions are not only presumed by analogy, but are ascertained by observation, to be valid wherever light can travel and gravity is obeyed—a science by which

Figure 1: Agnes Mary Clerke, 1842–1907 (after Macpherson, 1905).

> the nature of the stars can be studied upon the earth, and the nature of the earth can be made better known by study of the stars—a science, in a word, which is, or aims at being, one and universal, even as Nature—the visible reflection of the invisible highest Unity—is one and universal. (Clerke, 1902: 141).

Newton's supposition, that had been so fruitful, finally had empirical evidence from the stars' spectral lines. This unity, or uniformity, of natural laws made it reasonable to talk about the temperature and constitution of objects that no human could handle or manipulate. Lockyer described the same achievement as Clerke, but somewhat more tersely, as "… nature, in the regions we cannot get at, works in the same way as she does in the regions which we can get at." (Lockyer, 1887: 265).

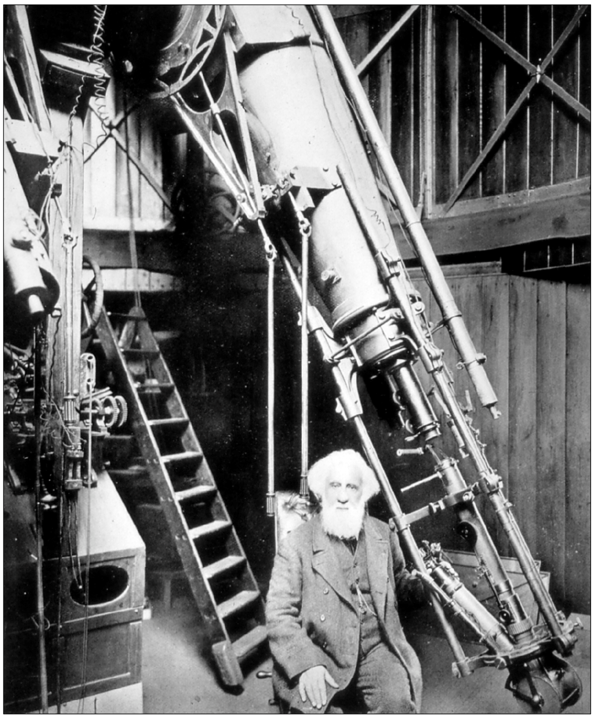

Figure 2: William Huggins, 1824–1910 (after Huggins and Huggins, 1909).

One of the consequences of the universal extension of natural laws was that different departments of knowledge suddenly overlapped. Without unity, the experiments of the chemist had no relevance for the calculations of the astronomer, and *vice versa*. Spectral analysis changed this, and what had seemed to be local, particular skills were now of cosmological significance. This is one of the reasons that many of the breakthroughs of early spectroscopy were conducted by physicist-chemist teams (such as Kirchhoff-Bunsen and Miller-Huggins). Again, Agnes Clerke described this transition in beautiful prose:

> … astronomy, while maintaining her strict union with mathematics, looked with indifference on the rest of the sciences; it was enough that she possessed the telescope and the calculus. Now the materials for her inductions are supplied by the chemist, the electrician, the inquirer into the most recondite mysteries of light and the molecular constitution of matter. She is concerned with what the geologist, the meteorologist, even the biologist, has to say; she can afford to close her ears to no new truth of the physical order. Her position of lofty isolation has been exchanged for one of community and mutual aid. The astronomer has become, in the highest sense of the term, a physicist; while the physicist is bound to be something of an astronomer. (Clerke, 1902: 142).

Clerke sung the philosophical praises of this new community of science, but in practice it was far from simple to suddenly move chemistry into the observatory. The era of astronomical practice as tranquil hours in the dark behind the eyepiece was over, replaced by an assault on the peace of all the senses. William Huggins (Figure 2) painted the picture vividly:

> Then it was that an astronomical observatory began, for the first time, to take on the appearance of a laboratory. Primary batteries, giving forth noxious gases, were arranged outside of one of the windows; a large induction coil stood mounted on a stand on wheels … together with a battery of several Leyden jars; shelves with Bunsen burners, vacuum tubes and bottles of chemicals, especially of specimens of pure metals, lined its walls. (Huggins, 1897: 8).

This was not the only collaboration between astronomers and chemists, as astronomical photography became widespread around the same time as the introduction of spectroscopy. The breakthroughs evolved together, showing how the techniques of one field could help advance another.

This need to draw on multiple fields certainly did not end rivalry among disciplines, however. William Crookes (Figure 3) cautioned that while interdisciplinary ventures were fine, one must still be wary:

> Inferences drawn from spectrum analysis per se are liable to grave doubt, unless at every step the spectroscopist goes hand in hand with the chemist. Spectroscopy may give valuable indications, but chemistry must after all be the court of final appeal. (D'Albe, 1924: 312).

The spectroscope may have brought uniformity to the laws of nature, but perhaps not so much to the competition among scientists.

The claim that all the Universe was governed by the same natural laws had a close cousin, that all the Universe was made of the same substances—the unity of matter. We are so accustomed to this idea now that it is hard to remember what a dramatic leap it was to claim that everything in existence was just like our little planet. But spectroscopy seemed to show that this was indeed the case. Lockyer noted the strangeness of gazing into distant reaches, only to find the familiar: "Where some, at all events, might have anticipated a new world of matter, we find likeness to the old." (Lockyer, 1887: 58).

The fact that spectral lines from distant stars could be matched up with material in terrestrial laboratories, down to mind-boggling levels of precision, seemed to dictate a complete uniformity of matter everywhere. James Clerk Maxwell (Figure 4) declared that the spectroscope had found hydrogen 'exactly identical' to our own far from Earth (Maxwell, 1890: 374), and Peter Guthrie Tait (Figure 5) stressed that these distant materials had all the same properties as terrestrial substances—there was no Arcturan carbon:

> … every atom of any one substance, wheresoever we find it, whether on the earth or in the sun, or in meteorites coming to us from cosmical spaces, or in the farthest stars or nebulae, possesses precisely the same physical properties. (Tait, 1885: 295).

To Maxwell, Lockyer, and most spectroscopists this was intuitively obvious upon seeing the spectral lines. The lines could not simply be a coincidence. A minority remained skeptical—could not other substances create similar looking spectral lines? Arthur Schuster (Figure 6) defended this position while expressing sympathy for the desire for unity:

> Most of us are convinced in our innermost hearts that matter is ultimately of one kind, whatever ideas we may have formed as to the nature of the primordial substance. That opinion is not under discussion. The question is not whether we believe in the unity of matter, but whether a direct proof of it can be derived from the spectroscopic evidence of stars. (Schuster, 1897: 212).

Proof or no, Maxwell, not Schuster, spoke for the majority. There seemed to be little room for doubt that the hydrogen in our drinking water was identical to that in the stars.

The uniformity of matter brought with it important consequences for cosmological theories, particularly the nebular theory. On this view, the Sun, Earth, and planets condensed from a single, self-gravitating primordial cloud. This suggested that the Sun and the Earth should be made of the same materials. This was a straightforward claim, but one impossible to test before the development of spectroscopy. The success of this prediction struck a strong blow for the nebular theory, and the Royal Institution's John Tyndall announced that "… in our day the [nebular] hypothesis of Kant and Laplace receives the independent countenance of spectrum analysis, which proves the same substances to be common to the earth and sun." (Tyndall, 1872: 32). Even more specifically, the structure of the dark lines suggested that the interior of the Sun was hotter than the exterior; again, a condition perfectly in line with Laplace's theory (Roscoe, 1873: 252).

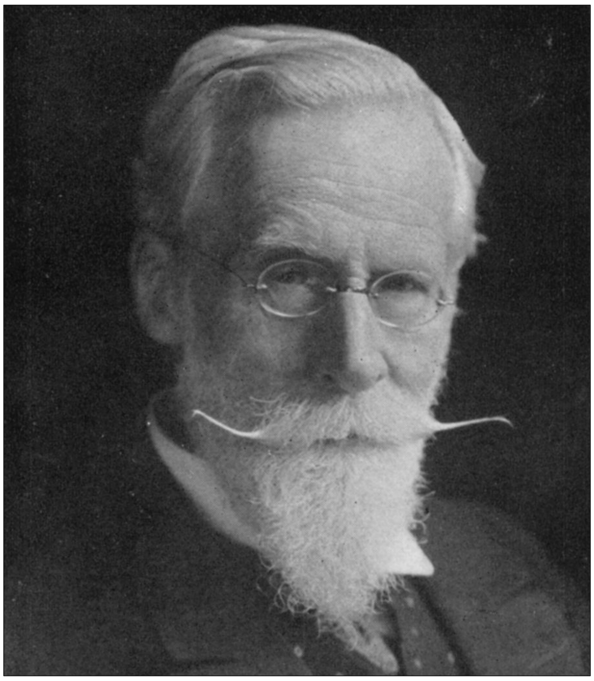

Figure 3: William Crookes, 1832–1919 (after D'Albe, 1924).

These realizations, combined with Huggins' observation that some nebulae were in fact completely gaseous, made plausible the leap that those clouds were our ancestors:

> The data furnished by spectrum analysis, too, favour the supposition of a common origin for sun and planets by showing their community of substance; while gaseous nebulae present examples of vast masses of tenuous vapour, such as our system may plausibly be conjectured to have primitively sprung from. (Clerke, 1902: 313).

The different types of stellar spectra were then inferred to be different stages in the evolution of stars from nebulae. All the pieces seemed to be in place for the

Figure 4: James Clerk Maxwell, 1831–1879 (after Campbell and Garnett, 1882).

nebular process—planets and stars sharing a common substrate, and a series of celestial bodies suggesting the collapse into a system. Huggins (1897: 107) was confident that there could no longer even be a question:

> There remained no room for doubt that the nebulae, which our telescopes reveal to us, are the early stages of long processions of cosmical events, which correspond broadly to those required by the nebular hypothesis in one or other of its forms.

One commentator assured his readers that the spectroscope's obvious support for the nebular hypothesis made it impossible to imagine any attack on the theory in the future (Clarke, 1873). Despite this, such attacks appeared quickly in the form of Lockyer's heterodox interpretation of astronomical spectra. Lockyer (1890) argued that the similarity among the spectra of stars, nebulae, comets, and terrestrial meteorites indicated that all those celestial bodies were nothing but clouds of small rocks, becoming bright through constant collisions. His theory was not widely accepted, but it did indicate the varying fortunes the nebular theory would have for decades to come. Regardless, its viability would rest for many years on the evidence of spectra.

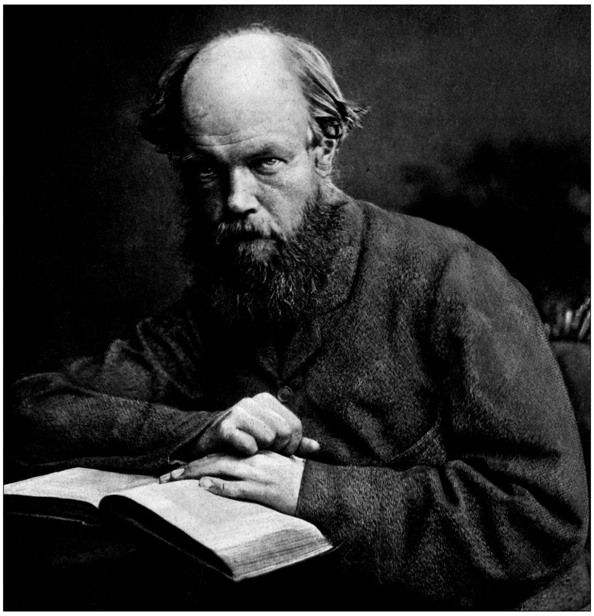

Figure 5: Peter Guthrie Tait, 1831–1901 (after Knott, 1911).

The uniformity of matter had further cosmic implications. Just as spectra linked the matter of our planet to distant stars, they seemed to also link us the same way. Lockyer (1900: 172) asked that since hydrogen, oxygen, nitrogen, etc., were "… common to the organic cell and the hottest stars … [so] is it possible that we have here a quite new bond between man and the stars?" Clerke expounded on the 'wonder' that our bodies were built from the dust of an ancient nebula:

> Custom can never blunt the wonder with which we must regard the achievement of compelling rays emanating from a source devoid of sensible magnitude through immeasurable distance, to reveal, by its distinctive qualities, the composition of that source … the application of prismatic analysis certified to the presence in the stars of familiar materials, no less of the earth we tread, than of the human bodies built up out of its dust and circumambient vapours. (Clerke, 1902: 372).

Not all the spectral revelations about life were positive, however. The high temperatures of the Sun indicated by its spectra finally destroyed William Herschel's proposal that it was inhabited by beings much like ourselves (Lockyer, 1887: 81).

3 ATOMIC THEORY

As much as spectroscopy spoke about the grandest scales of the Universe, it also revealed the smallest. It seemed to be the long-awaited window into the atom. Again, we are today so accustomed to thinking casually about atoms and their structure that it is important to recall how controversial such ideas were in the nineteenth century—it was not at all clear that atoms even existed. The spectroscope allowed a journey inward past the common appearances of the ordinary world into a deeper one: Crookes said it "… enables us to peer into the very heart of nature …" (Knight, 1967: 136), in particular, to see the atoms hidden beyond our vision.

For the first time scientists could experimentally investigate atomic phenomena, which otherwise drew criticism as matters only for speculation. One of the first implications of spectra was a perverse one—that atoms seemed to have an internal structure. This was opposed to the very concept of atoms (whose name literally meant that which cannot be cut) and many scientists at the time preferred to speak in a vague sense of 'molecules', meaning invisibly small but perhaps not indivisible particles.

The suggestion of substructure came from the multiplicity of sharp, discontinuous spectral lines associated with each element. Experimentalists concluded that those molecules must be compounds of some sort, with the different constituents each generating a different line (Schuster, 1881: 470-472). Maxwell pointed to the sharpness of the lines as the most important clue: "When the spectrum consists of a number of bright lines, the motion of the system must be compounded of a corresponding number of types of harmonic vibration." (Maxwell, 1890: 462). Numerous other investigators came to the same conclusion. If there were so many modes of vibration, there must be a number of different vibrators within the molecule (McGucken, 1969: 162-3).

This conclusion led to numerous attempts to calculate spectral patterns by mathematical manipulation of likely harmonic vibrations, notably by George Stoney (1871) and R.B. Clifton (1866). These attempts all failed completely, but strangely, physicists did not feel that was a problem. They did not need an exact description of the vibrations, just a broad assurance that it could be done in principle (Preston, 1880: 58). This is a common feature of 'so what' discoveries such as spectroscopy: much of their impact takes place in the realm of agenda-setting and imagination-firing, rather than solely contributing to discrete measurements.

Such implication of substructure for molecules was not particularly shocking, but the appearance of sharp lines even from materials that were apparently completely atomic (such as pure elements) proved unsettling. If atoms were, by definition, irreducible, how could they have a complex structure? Preston (1880: 56) wondered how "… to reconcile the proved indestructibility of the atom with its capacity for executing vibrations, as demonstrated by the spectroscope." Lockyer (1887: viii) argued that since we could observe spectral behavior in atoms that were associated with known compounds, perhaps it was time to change our notion of what an element was:

> … reasoning from the phenomena presented to us in the spectroscope when known compounds are decomposed, I had obtained strong evidence that the so-called elementary bodies are in reality compound ones.

Elementary atoms seemed not to be quite so elementary.

Lockyer (1887: 200-201) thought he could observe a process of elemental breakdown—which he called 'celestial dissociation'—in solar and stellar spectra. This was particularly visible, he said, in how spectra varied in different layers of the Sun, and he thought this hypothesis resolved various difficulties of interpreting spectra. He diligently quoted other physicists who were open to non-elementary elements (including Maxwell), and concluded that the formerly-inviolate atoms actually behaved "… like mixtures of organic compounds." (Lockyer, 1887: 301). This dissociation hypothesis became a major part of Lockyer's research agenda for the rest of his life, and much of his famous book *Chemistry of the Sun* (1887) is devoted to it.

Lockyer built on his dissociation hypothesis to form a vision of elemental evolution, where some primordial bits of matter change over time into the more complex elements we have on Earth. He explicitly drew on Darwin's ideas to justify his own, saying that chemical evolution "… derives its whole force from the fact that along many lines it runs parallel with the processes of development …" in the organic world (Lockyer, 1887: 262-263). He celebrated notions of evolution as "… the most profound revolution in modern thought which the world has seen." (Lockyer, 1900: 152).

Crookes followed a similar line of evolutionary reasoning, coining the term 'protyl' for the primordial material from which the elements were made. And, like Lockyer, he embraced terminology from organic evolution in an 1888 lecture:

> … elements owe their present stability in that they are the outcome of a struggle for existence, a Darwinian development by chemical evolution; that just as in the organic world we have "survival of the fittest," so here we have the "survival of the most stable" or possibly of the "most inert." (D'Albe, 1924: 324).

An alternative to non-elementary elements was the vortex atom, proposed by William Thomson (Lord Kelvin). These atoms were loops of ether that could vibrate in complicated ways, thus hopefully reproducing the spectral lines without discrete constituents (Preston, 1880; Silliman, 1963: 41). These vortices seemed to have the elasticity, complex behavior and indestructibility required of atoms, but again could not provide a quantitative explanation for the structure of spectra.

None of these atomic and evolutionary schemes came to any fruition, though they did form major research agendas for a number of late Victorian scientists, and no doubt made turn-of-the-century developments—such as the electron and radioactivity—much more sensible.

4 WHAT IT ALL MEANS

Finally, spectroscopy provided a launching pad for some grand philosophizing about the nature of things —why does the Universe exist? Why are we here? Lockyer waxed poetic about what spectra revealed about the relationship between man and nature:

> In this way, then, we have really been only continuing a train of thought, which has to do with Man's Place in Nature, in relation to the Sun's Place in Nature; and finding fresh grounds for thinking that the more different branches of science are studied and allowed to react on each other, the more the oneness of Nature impresses itself upon the mind. (Lockyer, 1900: 174).

This 'oneness' was a common theme of this category of reactions, no surprise given spectroscopy's implications for the unity of nature.

James Clerk Maxwell, in some articles for the *Encyclopedia Britannica* and in an address to the British Association for the Advancement of Science, drew attention to a different kind of oneness. He presented a complex argument beginning with the 'exactly identical' properties of molecular spectra from all over the Universe (Maxwell, 1890: 375). This identicality meant that molecules did not have the variation necessary for evolutionary processes to work, therefore they cannot have changed over time due to natural processes. This meant that

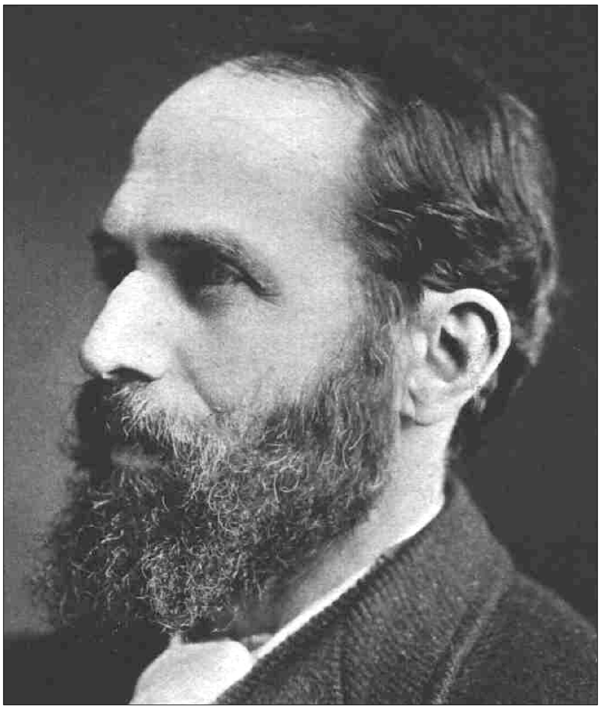

Figure 6: Arthur Schuster, 1851–1934 (courtesy: *Physical Laboratories*, 1906).

> … we have strong reasons for believing that in a molecule … we have something which has existed either from eternity or at least from times anterior to the existing order of nature. (Maxwell, 1890: 482).

Celebrating the unity of matter through all the ages and all the reaches of the Universe, Maxwell expressed his wonder that every molecule of hydrogen remained the same despite the ravages of time and nature:

> They continue this day as they were created—perfect in number and measure and weight, and from the ineffaceable characters impressed on them we may learn that those aspirations after accuracy in measurement, truth in statement, and justice in action, which we reckon among our noblest attributes as men, are ours because they are essential constituents of the image of Him who in the

> beginning created, not only the heaven and the earth, but the materials of which heaven and earth consist. (Maxwell, 1890: 377).

Thus Maxwell drew a theological conclusion from the regularity of spectra: not only was divine manufacture required to make molecules, but their perfection was an echo of the attributes of the Creator himself. Such sentiments from a scientist were not at all unusual at the time. The vast majority of Victorian scientists were religious and were quite comfortable linking the discoveries of science to their faith.

Another theological tone was sounded in a crucial early paper on astronomical spectroscopy where Huggins and Miller (1864) reported on their stellar observations. They noted that there was an irregular distribution of elements in the sky—some stars have more magnesium, some more iron, etc. Similarly, on the Earth some elements are found in uneven clumps:

> Whatever may have been the physical causes which may have produced this separation, we see abundant evidence of the advantage of this distribution in their application to the purposes of man—smallness in relative amount being compensated for by the accumulation of the material in denser deposits, which allow of their comparatively easy extraction to supply the wants of mankind. (ibid.).

It was taken as given by the authors that this useful arrangement of minerals was due to God's plan. And if this was so for our humble planet, the analogous arrangement in the stars must mean something similar:

> If this arrangement be admitted as designed in the case of the earth, is it going beyond the limits of fair deduction to suppose that, were we acquainted with the economy of those distant globes, an equally obvious purpose might be assigned for the differences in composition which they exhibit? [Spectral analysis] seems to furnish a basis for some legitimate speculation in reference to the great plan of the visible universe, and to the special object and design of [stars]. (ibid.).

The distribution of the elements in space, then, must also be part of a plan. But for whose use? Huggins and Miller (1864) noted that stellar spectra indicated that the elements most widely diffused were those associated with living organisms. Further, these distant stars appeared to have everything needed for life here on Earth—heat, light, etc. The conclusion seemed inexorable:

> On the whole we believe that the foregoing spectrum observations on the stars contribute something towards an experimental basis on which a conclusion … may rest, viz. that at least the brighter stars are, like our sun, upholding and energizing centres of systems of worlds adapted to be the abode of living beings. (Huggins and Miller, 1864: 433).

To summarize their argument: spectroscopy shows us that everything needed for life and civilization fills the Universe, in the same way that those things cover our Earth. God arranged the Earth for our use, thus the rest of the Universe must be filled with life as well. Huggins and Miller creatively combined their observations, the unity of laws and matter, and religion to paint a picture of a Universe teeming with beings much like ourselves (cf. Becker, 2010).

5 CONCLUSION

So what? Why were scientists excited about spectroscopy? It was not only the measurements and the concrete results of investigation. It was also the sense that spectral analysis was a great leap forward in human ability, and had set science on a path to even greater discoveries:

> Who could have dreamt ten years ago that we should so soon attain such an insight into the processes of creation? And yet, great though the results of spectrum analysis already are, they are but a tithe of the numerous questions which this branch of discovery has opened up—questions of such number and magnitude, that many generations of men will pass away before they are all satisfactorily answered. (Roscoe, 1873: 358).

Spectroscopy provided a window into deep-seated puzzles about the nature of science—confirmation of the assumptions of unity of laws and matter; ancient hypotheses that seemed startlingly relevant—the behavior of atoms; and the big questions—the relationship among man, God and the Universe. Spectroscopy was not a destination; it was a road that promised to connect humanity's most powerful speculations to a future of dramatic empirical investigation.

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Dr Matthew Stanley is a Professor in the Gallatin School of Individualized Study at New York University. His research interests include the history of physics and astronomy, the interactions between science and religion, and the use of history and philosophy of science in science education. He is the author of *Practical Mystic: Religion, Science, and A.S. Eddington* (2007). He has been featured on the History Channel and runs the New York City History of Science Working Group.