In *New Images of Musical Sound*, Robert Cogan explored the use of spectral photographs as a new analytic tool for music theorists\(^1\). Although Cogan's book went on to win the Society of Music Theory's Outstanding Publication Award in 1987, spectral analysis has seen little use over the past twenty-five years. Of the notable studies to make use of spectral images, most take a musicological approach as opposed to formal analysis of individual pieces of music. In that vein, articles like those by Albrecht Schneider and Cornelia Fales examining the sonic profiles of various instruments are enlightening, but do little to expand theorists' understanding of the music played by those instruments\(^2\).\(^3\).

Perhaps it is understandable that spectral analysis has not been more thoroughly embraced as a tool for understanding Western music. While Cogan outlines a system for describing and classifying all kinds of music with spectral photographs, what spectral imaging reveals most dramatically is timbre. There is a section of *New Images of Musical Sound* devoted to analyzing Beethoven's Piano Sonata in E, but timbre is not as structurally significant to Beethoven's compositions as harmonic progression. The same is true for the vast majority of pieces written in the Western musical tradition. Good tone quality is an important part of each individual performance, but harmony is the preeminent structural component.

There are, however, counterexamples. In *The Liberation of Sound*, Edgard Varèse stated that ideally in his compositions, “[t]he role of color or timbre would be completely changed from being incidental, anecdotal, sensual or picturesque; it would become an agent of delineation...and an integral part of form.”\(^4\) Timbre is more than just a matter of sound quality when it comes to Varèse; it is a critical structural component. Not only is timbre uniquely important in these works, harmony can be entirely absent. Completed in 1931, *Ionisation* is widely recognized as the first significant percussion ensemble piece by a western composer. There is no melody. There is no harmony. Timbre is

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In the words of Varèse protégé Chou Wen-chung, *Ionisation* is “the first and the most consummate work to explore the structural value of all non-pitch properties of sound without electronic means.” While only a modest 91 measures long, its sound is epic, featuring 13 players and some 40 instruments. Chou and Jean-Charles François have both published detailed analyses. Each acknowledges the vast importance of timbre to the work, but neither is willing to address the nature of *Ionisation*’s sound directly.

François' *Organization of Scattered Timbral Qualities* uses vague descriptors like “rather low”, “rather high”, and “wide ranging”. In explanation, he states that timbre “cannot be grasped easily, nor transcribed into a general description; it escapes the elaboration of a continuum.” Chou's analysis runs into a similar problem. Questioned by Elliott Carter following his April 1977 presentation, Chou elaborated on the difficulty of analyzing timbre:

> I must say that the problems of definition of terms I have used here – timbre, sonority, texture – are partly responsible for my not having written on this subject earlier. One has to deal with these questions quite decisively before we can proceed in a definitive way. But this may take some time. I do not see how I am going to analyze this work, even tentatively, except by going ahead in an instinctive way. Thus, I have not given you a precise definition of timbre at this time, but I did point out that the work is based on Varèse's conception of articulative and vibratory characteristics...I will have to depend on people who specialize in this type of analysis to tell me whether what my ear tells me instinctively as a musician is the right thing or not.

Seven years later, Robert Cogan published *New Images of Musical Sound*. Groundbreaking though it was, Cogan's method of spectral analysis was limited by the technology of its time. For his work, Cogan used a thirty-three-millisecond fast Fourier transform instrument with a five-octave limit, a scan control unit, and two tube displays with a 15 frame per second refresh rate. The first display offered a live view of the Fourier transformation, while the second allowed an individual frame to be

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7 François, 49.
8 Chou, 84.
frozen and photographed for analysis. Cogan openly acknowledged the limitations and flaws in this system, admitting that the hardware and five-octave limit caused some distortions and did not allow proper context for sonic events. Full-scale formal analyses of compositions would have been extremely difficult to produce using technology from 1984, if full-scale analyses were even possible.

The final paragraph of *New Images of Musical Sound* reads,

> One can only look forward with great anticipation to future developments of this technology. Ideally, every complete-context spectrum analysis should cover the entire audible space range, respond to the full audible dynamic range, and precisely display the relative loudnesses of all the spectral elements more or less as they are received and perceived by the human auditory system. The technological advances have been large, but several steps are still needed before that ideal can be attained. Moreover, these analyses are not merely technical. Progress in this field depends upon the continuing coordination of technology with conceptual science and artistic understanding.  

Cogan's progress has come to pass. Today, exponentially more powerful software does the work of hardware scan control units and display tubes. Superficially, spectral images are not vastly different. Time is represented horizontally with an adjustable scale along the x-axis. Frequency is represented vertically with a similar scale along the y-axis. On the outdated monochrome display tubes, sound at a given frequency was represented by a point of light. Continuous sounds could produce lines, bands, or waves. The intensity of sound was indicated by brighter light. Modern displays make use of color instead of light, but with similar results. Brighter, whiter lines represent stronger frequencies. These are relatively superficial differences, but serious advances have been made in scan control. Modern software allows for precise adjustments to both the time and frequency axes. It is possible to zoom in on tiny fractions of a second or even individual frequencies. While this may not be as important for many instruments, it is critical for percussion, where attack and decay can be sudden. Perhaps the most exciting improvement of software over hardware is one Cogan did not anticipate. Audio filtration is not a new concept, but modern computers take it to a new level. Software can filter frequencies manually, or noise reduction can be trained using an audio sample.

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9 Cogan, 156.
These advances make it possible to pick individual instruments out of a crowded recording and perform spectral analysis in a new way.

All spectral analysis requires source audio. When it comes to *Ionisation*, a number of excellent recordings are available. For a piece that relies so heavily upon instrument selection and timbre, the source audio can have a significant impact on analysis. To choose the most appropriate audio source, theorists should consider which most closely reflects the composer's intent. Fortunately, one recording of *Ionisation* was supervised by Varèse himself. As such, this study will use the El Records 2007 digital re-release of EMS 401, the 1950 recording bearing Varèse's fingerprints.\(^{10}\)

Analyzing the individual instruments of *Ionisation* is an important step toward understanding the construction of the piece as a whole. Both François and Chou organize the instruments into groups that play various roles in defining textures and sections. As Chou makes explicitly clear in his concluding remarks:

> A crucial principle is the grouping of instruments of the same family or of compatible articulative and vibratory characteristics so that a group of such instruments (whether manned by one or more players) is capable of changes in register and timbre and yet remains identifiable as a single part or line.\(^{11}\)

As previously mentioned, both major analyses categorize *Ionisation*'s instruments, but neither study offers any evidence or for why the groups hold together beyond the materials of their construction. For example, if an instrument is made of metal, it goes in the “metal” group. If an instrument has a membrane (drum head), it goes in the “membranes” group. This method of organization makes sense intuitively, but the construction material does not necessarily describe how an instrument functions timbrally. Interestingly, François emphasizes the importance of understanding each instrument individually, stating that “…each instrument has its own fixed sound identity which is a composite relationship of its pitch, timbral quality, length of decay, speed of articulations, and metrical/phase characteristics.”\(^{12}\)

Spectral analysis provides concrete evidence that can inform a more accurate

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11 Chou, 71.
12 François, 60
understanding of each instrument and how it fits into the piece as a whole. Spectral images in the following section are presented with time and frequency axes calibrated to provide useful detail for each sonic event without any alteration to content.

Chou places the triangle in his “Metal” group. Although François retains most of Chou's categories, he distinguishes between Clear and Complex Metals. In *Organization of Scattered Timbral Qualities*, the triangle is considered one of the former. Spectral imaging (Figure 1) shows the EMS 401 triangle appears as a series of clear, thin lines ranging from approximately 2500 Hz – 10400 Hz, with very little additional noise. Each partial is quite distinct. Chou recognizes the triangle as the “highest” metal instrument, and borrows from gamelan terminology to describe its function as “colotomic”. While other instruments in *Ionisation* have higher partials, the triangle has one of the highest fundamental pitches. Additionally, the significant lack of noise, especially in the higher frequency band, gives the triangle a uniquely pure sound. The combination of high pitch and pure tone allow it to cut through the rest of the spectrum to be heard and serve a colotomic, or marking off, function.

The anvils have a lot in common with the triangle. Chou and François sort them into the Metal and Clear Metal groups, as each did with the triangle. Like the triangle, anvil appears spectrally (Figure 2) as a series of thin, clear lines. By contrast, however, the anvil has noticeable diffuse bands of noise, particularly at higher frequencies. Distinct frequencies appear from approximately 2900 Hz – 12500 Hz. More diffuse “ring” from the anvil sounds from 11 kHz and rolls off as it approaches the upper audible limit. Unlike the triangle, anvil attacks are enhanced by these noise bands and manifest very distinct entrances in the spectral images. In the course of structural analysis, Chou cites similarities between anvil and cowbells for the smooth transition into measure 51. While far from identical, Chou is quite right to recognize similarities between the two instruments. The cowbell (Figure 3) is much less distinct, but the pattern of compact frequencies and a

13 Chou, 31.
14 Chou, 49.
15 Chou, 33.
Figure 1 - Triangle

Figure 2 - Anvil
diffuse background relate it closely to the anvil. Interestingly though, there is not a clear “fundamental” pitch. Instead, there is a broader, more diffuse band from 450 Hz – 700 Hz that makes up the “bell” sound. Higher ring from the instrument continues from the bell tone up to approximately 8500 Hz. With this lower range it is, however, difficult to accept Chou's description of cowbell as a “high metal timbre”. The role of the cowbell in Ionisation is primarily subordinate to the bass drum of Player 1. Perhaps this is why cowbell is entirely omitted from Organization of Scattered Timbral Qualities.

In spite of this omission, one improvement François makes over the Chou analysis is the distinction made between Clear Metal instruments and Complex Metal instruments. While the Chinese cymbal (also referred to as the grande cymbale Chinoise or crash cymbal, shown Figure 4) bears little resemblance to the triangle, anvil, or cowbell, Chou places them all in the nondescript “Metal” group. The Chinese cymbal shows none of the distinct lines of the Clear Metal instruments. Instead, the spectral image it creates is that of a dense, diffuse sound mass. François recognizes this difference. Frequencies between approximately 350 Hz and 8000 Hz are activated, with significant roll off at the higher end of the spectrum. The sound is remarkably even across the active section, with no significant peak frequencies.

The suspended cymbal is notably similar (Figure 5). Also a Metal/Complex Metal instrument with a nearly identical range, the suspended cymbal fades more evenly from its lowest frequencies as compared to the Chinese cymbal. The result is an audibly more focused sound that is perceived as being “lower” than the broad spectrum of the Chinese. It is also likely the reason Chou describes the suspended cymbal as being in the same register as the bass drum, although this is not strictly true.

The crash cymbals (also listed as cymbales or hand cymbals, shown in Figure 6) have a slightly different spectral footprint, but are still classified as both a Metal and Complex Metal by Chou.

16 Chou, 45.
17 François, 69.
18 Chou, 51.
Figure 3 - Cowbell

Figure 4 – Chinese Cymbal
Figure 5 – Suspended Cymbal

Figure 6 – Crash Cymbals
and François. Their spectral image is an even block ranging from approximately 1100 Hz – 10400 Hz, including a smaller cluster at the lower end of the range. According to Chou, the crash cymbals add a “snare-like quality” to the bass drum at measure 9. Spectral images show similarities between the crash cymbals and the snare component of instruments like the tarole, tambour militaire, and the snare drum. While the membrane instruments all conform to a strict spectral model, the commonalities between the component sounds are enough to confirm Chou's analysis.

Having examined each of the cymbals used in Ionisation, one particular observation must be made about the difference between intuitive and spectral analysis. Cymbals are often one of the most dramatic instruments encountered in classical music. The single crash in a piece of music is more often than not at the climax – an explosion, waves dashing a ship against the rocks. Cymbals are typically perceived as loud and startling. The intuitive expectation is that cymbals would be similarly notable from a spectral standpoint. Already, that expectation has been proven inaccurate. Cymbal attacks are not nearly as clear as one would expect. Their power comes from exciting a wide, diffuse band of frequencies simultaneously, but their sustain and gradual decay also makes them less prominent visually. The diffuse nature of cymbals does not decrease their value or importance to the composition as a whole, but it does underscore a key difference between intuitive expectation and measured analysis.

The final instruments both articles classify as metals are gong (Figure 7) and tam-tam (Figure 8). Chou describes them as providing the characteristic sound of Texture I. They certainly have common elements, in particular, their massive sustain. The decay for either instrument is only visible in large-scale spectral images. There are, however, significant differences between the two. For one, the vibration of the tam-tam is clearly visible in each image, while the gong produces a clear, consistent band. More significant to the role each plays, the tam-tam covers the spectrum from the very lowest measurable frequencies up to approximately 160 Hz or 250 Hz, depending on which tam-tam is in

19 Chou, 39.
20 Chou, 30.
Figure 7 – Gong

Figure 8 – Tam-Tam
question, low or high. By contrast, the gong appears as a very clear, compact band from approximately 265 Hz – 350 Hz. The gong generally creates one less prominent, but distinct overtone band from 600 Hz – 800 Hz. As a pair, the two demonstrate the difference between instruments that are alternately compact or diffuse, but otherwise alike. François categorizes both as Complex Metal instruments, but the compact nature of the gong suggests that the Clear Metal category might be more appropriate.

While the tam-tam is without question the lowest metal sonority, Chou labels the bass drum (Figure 9) as the lowest Membrane.21 As with the metals, François distinguishes between Clear Membrane and Complex Membrane instruments. Bass drum falls into François' Clear Membrane category. Like the tam-tam, the vibration of the bass drum is visible in spectral images and it ranges from the core sound around 60 Hz down to the bottom end of the spectrum. The core itself is relatively compact and noticeably hotter than the rest of the image from 60 Hz – 160 Hz. Ring from the drum extends as high as 7000 Hz, but with increasingly short decay times and decreasing prominence overall at higher frequencies. The core sound and the ring from the drum are contiguous through the active range, but remain distinct from one another visually.

Bongos illustrate a similar pattern as membrane instruments (Figure 10). A core sound is visible from approximately 95 Hz – 150 Hz for the lower drum, with a ring extending upwards to 1000 Hz. The higher drum is almost identical, with its core appearing from 150 Hz – 210 Hz. It is worth noting that these ranges are considerably lower than bongos are typically tuned today, and create a significantly different sound in old recordings as compared to modern ones.

The final instrument listed as a Clear Membrane is the tenor drum, which is listed as the caisse roulante in the score, and elsewhere referred to as the side drum (Figure 11). Like the other membranes, there is a core sound that forms a band from approximately 100 Hz – 200 Hz. The ring, as with previous examples, activates frequencies above the core. In this case, the sound of the drum as a whole spans 100 Hz – 650 Hz. According to Chou, François, and others, the tenor drum is meant to be

21 Chou, 31.
Figure 9 – Bass Drums

Figure 10 - Bongos
played without snares. In spite of this, snares can be heard rattling on the recording. It is possible that even with the tenor drum's strainer in the off position, the snares continued to make noise. Whether this is the case or not, the rattle from the snares is also visible in spectral images extending upward from the main “drum” sound. The snare sonority is evenly diffuse, with its main density visible 1300 Hz – 8000 Hz. This calls into question its position in both analyses by Chou and François as a Membrane and a Clear Membrane, respectively. Instead, it may fit more appropriately into their categories for Snares and Complex Membranes.

The prototypical snare instrument is the snare drum, listed in the score as the caisse claire (Figure 12). Also in the score is the tarole, which is a particular type of snare drum with a shallow shell (Figure 13). Both are classified by Chou and François as Snares or Complex Membranes. Although the tarole is supposed to be a thinner drum, both their sounds in the recording and their appearances in spectral images are almost indistinguishable from one another. Both instruments exhibit a core sound that creates a band from approximately 80 Hz – 150 Hz, although this band is more diffuse and less prominent a component of the overall sound than the cores of other membranes. In light of this, Chou's statement that the snare and bongos are in the same register is reasonably accurate, but the claim that the tarole “raises the register of the snare sonority” is questionable.^[22 Chou, 51.]

In addition to the core drum sound, the snare drum and tarole images also contain a diffuse band representing the rattle of the snares. A majority of snare rattle is contained in the spectral band from 1000 Hz – 8500 Hz, but frequencies remain active on a lower scale from 500 Hz – 15000 Hz. Softer attacks on either instrument and passages played with mallets instead of wooden sticks produce less drum sound, but still activate the snares. In the very first measure of Ionisation, a roll on the caisse claire is played with snares turned off. Interestingly, the lack of clear attacks activates the rattle of the snares as with the tenor drum, but produces little if any core sound.

The last instrument Chou and François both sort into their Snare and Complex Membrane
Figure 11 – Tenor Drum

Figure 12 – Snare Drum
Figure 13 – Tarole

Figure 14 – Tambour Militaire
groups is the parade drum, or tambour militaire (Figure 14). Drum sound from the tambour militaire is audible, but there is no compact core visible in the spectral images. Instead, the parade drum resembles the snare drum without snare more closely than the tarole or snare drum with stronger attacks. Chou names the tambour militaire as the characteristic instrument of Texture II.\(^{23}\) In a crowded spectrum, the lack of compact frequencies and distinct fundamental could prevent the parade drum from carrying out this role. Instead, it only competes with the maracas for the upper part of the spectrum, and the snares activate a much wider band.

Except for Wood instruments, this is the point where Chou and François' instrument groups begin to diverge. Chou recognizes Rattle-Scratcher (multiple bounce), Air-Friction (varying intensity), and Keyboard-Mallet (tone cluster) instruments as independent groups. Instead of tone clusters, François describes one category of instruments as being Pitched at rehearsal number 13. His remaining two groups, Rattles and Modulations, overlap with other categories instead of being self-contained. For example, François describes maracas as existing in both the Wood and Rattles groups, while Chou considers them a Rattle-Scratcher instrument alone.

While cross-categorization of instruments may be useful, the spectral image produced by the maracas is fairly simple (Figure 15). Ranging, from 2700 Hz – 12000 Hz, the maracas produce a diffuse band with small breaks at 4600 Hz and 6300 Hz. Multiple attacks from multiple bounces are not visible, although the full intensity of the sound does not arrive until shortly after the initial attack. Chou describes the maracas as adding a “snare-like quality” with the cymbals at measure 9.\(^{24}\) While they do not activate the higher and lower frequencies like the snare drum and the tarole, the maracas' spectrum is completely contained by the bounds of the snare instruments. Their diffuse properties are otherwise similar.

Like the maracas, Chou and François place the guiro into the Rattle-Scratcher and Wood and Rattles groups (Figure 16). Compared to the maracas, the guiro bears a closer resemblance to a snare

\(^{23}\) Chou, 31.
\(^{24}\) Chou, 39.
Figure 15 – Maracas

Figure 16 – Guiro
sound, although neither analysis comes to this conclusion. The guiro's attack is much clearer than the maracas, with a wide range from 625 Hz – 10300 Hz. As diffuse as the image is, the intensity of sound is not evenly distributed across the spectrum. The signal is significantly hotter and the sustain greater at a core band from 1500 Hz – 6000 Hz. Overall, the image forms more of a bell curve than an even, vertical line.

By contrast, the castanets appear precisely that way spectrally, as thin, distinct, vertical lines (Figure 17). Like the previous two instruments, the castanets are sorted into Rattle-Scratcher, Wood, and Rattles groups. While the individual events are diffuse from 3300 Hz – 10 kHz, they feature a weighted core from 1750 Hz – 3300 Hz. Each attack is very distinct and each decay is shorter than any other instrument. By Chou's description, the castanets are one of three instruments that make up the characteristic sound of Texture III. The clear definition of individual notes through distinct attack and rapid decay may aid in this function. Contrary to Chou's organization, however, no rattle or multiple bounce is visible in the spectral images.

The most similar image belongs to an instrument both Chou and François list in their respective Wood groups, the claves (Figure 18). Like the castanets, the claves feature a clear attack, but a far more prominent core sound. The core, which is much stronger and more compact than the ring of the instrument extends from approximately 2500 Hz – 2750 Hz. The additional spectrum activated ranges from 2250 Hz – 10 kHz. While the ring is audible in the outlying frequencies, the core makes up almost all of the characteristic sound. Chou claims that the claves mediate the cowbells and tambourine pairing and the maracas and snare drum pairing at measure 38. While the core sound of the claves falls between the cores of the cowbells and the jingle of the tambourine, it is difficult to explain how they might mediate the maracas and snare.

The prototypical Wood instrument is, of course, the woodblock (Figure 19). In the score, Varèse specifies 3 blocs Chinois, which bear closer resemblance to modern temple blocks than wood

Figure 17 – Castanets

Figure 18 – Claves
blocks. Varèse also distinguishes between clair, moyen, and grave, but the spectral images are not vastly different. Each block is relatively diffuse with a clear attack. The spectral image itself forms a sail shape, activating frequencies from approximately 700 Hz – 11000 Hz. Like the triangle, Chou assigns the woodblocks a marking-off function. While the clarity of attacks help provide definition to the spectral events, there is little else to enable the wood blocks to cut through the texture. In order to function as a marking-off instrument, the wood blocks have to be played without significant noise interference. Appropriately, these events, which Chou often describes as cadential, occur in isolation from other rhythmic activity.

The instrument most similar to the woodblock is arguably not an instrument at all. François does not address the rim shot as a unique event, different from other notes. Chou considers it a Metal sonority. The rim shot is a performance technique that combines drum stick contact on both the rim and head of a drum simultaneously. As played in the current recording of Ionisation, the rim shot notes are almost certainly played simply on the rim. From a spectral standpoint, the rim notes look remarkably like the woodblock (Figure 20). The rim images form a diffuse fan shape from approximately 1000 Hz – 14 kHz, with a majority of the sound from 2200 Hz – 7500 Hz. The ring from the rim lasts longer than the majority of wood instruments, presumably because the shell and heads of the drum provide more resonance. Still, the rim resembles the wood blocks more than any Metal instrument. By Chou's explanation, the rim shot is associated with timbral instability “perhaps...because of its own lack of definition in timbre.” On the contrary, rim attacks are much more clearly defined than a number of other instruments. The rim is relatively diffuse, but so are many other instruments. If such an association truly exists, it has nothing to do with the spectral properties of the rim.

The final distinct Wood instrument, as defined by both Chou and François, is the slapstick, or

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26 Chou, 47.
27 Chou, 58.
Figure 19 – Woodblocks

Figure 20 – Rim
whip (Figure 21). According to Chou, the exclusive function of the whip is to mark off sections.\(^{28}\) Here, the whip is noteworthy for its wide range, from 350 Hz all the way up to 12000 Hz. The attack is always clear, and the decay is almost immediate. The whip's sound is both diffuse and even across its entire spectrum. There appears to be some additional ring from 1350 Hz – 8500 Hz, but these frequencies are no more prominent than any others in the attack.

A similar spectral shape is produced by the tambourine, which is classified as a Rattle-Scratcher instrument by Chou and a Complex Membrane by François (Figure 22). François' comparison between the tambourine and snare drum is apparent, as the tambourine is comprised of both a drum head and jingles the way the snare drum is made up of drum heads and snares. Like the snare instruments, the spectral images of the tambourine demonstrate both independent sounds. Ring from the tambourine's head spans from about 200 Hz – 2900 Hz, while the jingles are visible from 2900 Hz – 15 kHz. While the lower frequencies are diffuse, some of the jingle frequencies are considerably more compact. True to Chou's observation, the tambourine bridges metal and membrane timbres at measure 38.\(^{29}\)

Along with castanets and sleigh bells, tambourine is one of the characteristic sonorities of Chou's Texture III. The sleigh bells, while considered a Rattle-Scratcher instrument by Chou, resemble François' Clear Metal instruments much more closely (Figure 23). From a spectral standpoint, the sleigh bells produce a series of thin, compact bands from 2400 Hz up to 10200 Hz. Subtle hints of shimmer in the bells can be heard all the way up to 15000 Hz. Unlike other metals, the attack is not unified. Different compact bands are activated at different points in each attack. The decay times are similarly variable across the spectrum. While the spectral bands are more compact than the diffuse swaths created by Complex Metal instruments like the crash and suspended cymbals, the variation in attack and decay times introduce a complexity not present in other Clear Metals.

Some of the clearest metal instruments are not classified as such by either Chou or François. The chimes, described as a Keyboard-Mallet instrument by Chou and Pitched by François form a

\(^{28}\) Chou, 47.
\(^{29}\) Chou, 44.
Figure 21 – Whip

Figure 22 – Tambourine
striking spectral image (Figure 24). Each attack is crystal clear and made up of bright, extremely compact bands. The initial mallet contact produces a small degree of diffuse noise, but this only serves to enhance the impact of each attack. The lowest frequencies activated in the broad sweep of the chimes range as low as 200 Hz, but the strongest, clearest fundamentals exist from approximately 1575 Hz – 3000 Hz. In light of the large number of compact frequencies activated, the chimes can hardly be considered pitched. By comparison, the anvil and triangle are closer to representing individual pitches.

The instrument most like the chimes is the glockenspiel à clavier, which rather than a simple glockenspiel, is intended to be a celesta (Figure 25). Like the chimes, spectral images of the celesta show bright, compact spectral bands over a relatively wide range. The celesta produces much more diffuse noise connecting the bands, and frequencies decay progressively more quickly as they approach the upper boundary of the spectrum. The lowest bands appear around 1000 Hz, but the most intense centers on 4500 Hz. In general, the celesta is less prominent and more diffuse than the chimes.

The most diffuse Keyboard-Mallet and Pitched instrument defined by Chou and François is undoubtedly the piano (Figure 26). Spectrally, the piano appears as a large, diffuse block with minimal decay. No frequencies stand out significantly more than any others. For an instrument that is typically functions in melodic and harmonic contexts, the piano is shockingly even and diffuse. Interestingly, the low piano does not seem to extend above 3000 Hz, but does extend all the way through the lowest measured frequencies. Diffuse though it may be, the piano's attacks are quite clear.

Possibly the least distinct instrument is the string drum, or lion's roar (Figure 27). Like the piano, the string drum is both even and diffuse. Unlike the piano, the attack is virtually nonexistent. The string drum itself is often constructed of a single drum head with a piece of rope or string attached to the center. It is played by pulling a damp cloth along the rope, away from the drum. The friction between the cloth and the rope creates vibrations and sound from the head. As such, sound is only produced when a critical amount of friction is created in the rope. The variable friction created by
Figure 23 – Sleigh Bells

Figure 24 – Chimes
Figure 25 – Celesta

Figure 26 – Piano
moving along the rope causes a minor shift in pitch. It is this property François singles out in his categorization of the string drum as a Modulator. Chou considers the method of sound production more important in his description of the string drum as an Air-Friction instrument. Whatever pitch change is present, it is not readily visible. Instead, the diffuse spectral image extends from approximately 140 Hz – 12000 Hz.

The most striking and dominant instrument in all of Ionisation belongs to the same Air-Friction and Modulator instrument groups. Sirens are the most obvious feature when viewing spectral images of the entire piece (Figure 28). Changing pitch in increasing and decreasing intensities, the sirens appear as compact, graduated bands that rise and fall like waves across the spectrum. In each case, the fundamental pitch is the most intense. Each successive band representing a partial above the fundamental is thinner and represents less sonic intensity. As many as a dozen overtone bands are visible at any given time, each perfectly congruent to the fundamental. At their lowest, siren frequencies die out around 350 Hz. Overtone bands fade to nothingness at approximately 8500 Hz. It is both striking features like the siren and less obvious images like the string drum that come together to help define the textures and structures that give meaning to Ionisation on a larger scale.

Both Chou and François recognize three broad timbral patterns that help organize Ionisation. François explains that the system of timbral patterns “is particularly important because it will serve as a basic model for the organization of the piece at all levels.”30 While Chou's three textures and François' three structures often describe the same material, their definitions are slightly different.

Texture I “closely resembles the envelope characteristics of a gong sound.”31 By Chou's description, it demonstrates attack, steady state, growth, and decay. In more specific terms, Texture I is defined by the instruments that make up the first four measures of the piece. François' analogous Structure I is described as being made up of opposite timbres, such as low skins and resonant low metals, mixed with modulated sounds in the background. François' more general descriptor is

30 François, 52-53.
31 Chou, 30.
Figure 27 – String Drum

Figure 28 - Siren
“rather low”.

Texture II is meant to feature bongos and maracas in the higher register and deep bass with crash cymbals in the lower register. Chou estimates Texture II as being higher than Texture I. The snare is the characteristic sonority. François seems to base his Structure II on the snare sonority as well, defining it by fast, sharp, articulated sounds with short to medium decay and two or three opposing timbres. Echoing Chou's contrast, François describes Structure II as “rather high”.

Chou says very little about Texture III, except that he views it as the highest of the three with rattles as the characteristic sonority. Meanwhile, François' Structure III takes on a markedly different description, a very loud, monophonic tutti made up of a mixture of timbres. Instead of calling it the highest of the three, François' Structure III is listed as “wide-ranging”.

Chou and François recognize the first eight measures of Ionisation as the introduction of Texture I and Structure I, respectively. Looking at the spectrum, the first measures resemble Chou's comparison to a gong sound fairly well (Figure 29). The attack and steady state are easy to see, although the later attacks from the bongos, tarole, snare drum, and bass drums undermine the gong template somewhat. François' explanation of Structure I matches more closely. The low and modulated sounds are readily evident, although the higher frequencies activated by the snare instruments are omitted.

Both analyses also mark measure 9 as the beginning of Texture II and Structure II. The spectral image for measures 9 – 12 is obviously different, and requires distinction from the introductory passage (Figure 30). A key difference is the activity in the higher register. Contrary to Chou's explanation, it is the tambour militaire in conjunction with the maracas, rather than the bongos, that activates these frequencies. Similarly, the crash cymbals do little, if anything, to lower the tessitura, although the snare sonority is certainly prominent. While it does not address the ranges of the instruments, François' definition of Structure II is much more accurate. The description of fast, sharp, articulated sounds is highly characteristic of the section, and the bass drum and bongos can be readily described as François'
opposing timbres.

From measure 13, Chou and François begin to diverge in their analyses. Where Chou sees his Texture III carry on from 13 – 21, François divides the measures into four bar phrases of Structure I and Structure II. As vague as the description of Texture III is, the first four bars closely resemble François' Structure I (Figure 31). The next measure and a half seem to match Structure II as well, but midway through measure 18 the timbre changes (Figure 32). Instead of the fast, sharp, diffuse attacks, compact highs begin to appear. Here, Chou's description of Texture III as the highest of the three textures gains credibility. The upper frequencies are stronger, and the compact high frequencies lend additional weight to the upper end of the spectrum. Additionally, those compact highs come primarily from Chou's rattles: the sleigh bells, castanets, and tambourine.

François observes a continuation of Structure II from measure 21 all the way to measure 38. Meanwhile, Chou suggests a combination of all three textures is present, with Texture I being somewhat diluted. Viewing the spectral image from François' perspective, the passage has a lot in common with Structure II (Figure 33). Sections of diffuse snare-like sound alternate with the more compact, top-heavy material. By Chou's description, these are the characteristics of Texture II and Texture III. Meanwhile, the characteristic gong and tam tam sonorities of Texture I are less significant, but visible. The siren from Texture I is also apparent in the final measures.

From measure 38 to measure 44, François introduces his conception of Structure III, the monophonic tutti, in conjunction with Structure II. Interestingly, this mirrors Chou's interpretation of the section as Texture II and Texture III in spite of the differences between their definitions of structures and textures. This section is particularly dense and diffuse. François' description of a monophonic tutti seems to match well with what can be seen spectrally (Figure 34). Of Chou's textures, Texture II fits closest. There are compact traces in the upper end of the spectrum, left by the claves, but the accentuated highs of Texture III appear to be largely absent.
Figure 31 – mm. 13 – 16

Figure 32 – mm. 17 – 20
In the following measures from measure 44 to measure 50, Chou maintains the presence of Texture II and Texture III, with elements of Texture I resurfacing in the guise of the string drum and bass drums. Meanwhile, François indicates the first solo occurrence of Structure III. The spectral image retains a strong sense of continuity from the previous one (Figure 35). More compact high frequencies are present to enhance that aspect of Chou's Texture III analysis. François' exemption of Structure II here appears to be based on the score as notated. While the previous section featured independent rhythmic lines on tarole, tambour militaire, and tenor drum, those instruments play in unison with the rest of the ensemble here. From a spectral standpoint, there is very little difference. Broad spectral images remove much of the rhythmic detail. In this case, the images provide little incentive to differentiate between the material from measures 38 – 43 and measures 44 – 50.

From this point, measure 51, to the end of the piece, Chou describes the remainder of *Ionisation* as all three textures together. François parses the same music into much smaller sections, the first of which extends from measure 51 to measure 65. Here, he describes the music as a combination of Structure I and Structure II. As before, the gong and siren sonorities represent Structure I and Texture I. By contrast, though, the anvil and triangle do not fit into François' established structures. While Chou offers little additional information to break up the rest of the material, he does notice a “markedly different overall texture” at measure 56. François makes no such distinction, but the timbral shift is readily visible in the spectral image as the rapid, diffuse bands make their entrance (Figure 36). With the combination of wide, diffuse bands; compact, high frequencies; and gongs and sirens, all three of Chou's textures are represented.

François breaks up the next several measures individually. As previously mentioned, Chou's analysis of a combination of all three textures continues unabated. According to François, measures 66 and 68 are Structure III. Measure 67 is Structure I and Structure II. This alternation of structures is quite clear in the spectral image (Figure 37). In fact, the clear cut transitions are quite striking. The

32 Chou, 33.
Figure 37 – mm. 66 – 68

Figure 38 – mm. 69 – 71
questionable aspect of this is whether measures 66 and 68 qualify as a monophonic tutti. Arguably, they bear a closer resemblance to the snare sonorities of Structure II. However, Chou's three textures describe measure 67 well. Continuing the alternation of structures, François describes measure 69 to measure 71 as a return of Structure I and Structure II combined. Measure 69 is not as close to measure 67 as measure 68 is to measure 66, but there is certainly enough consistency to merit the analysis.

After just three bars, François analyzes another single measure, 72, independently. This time the individual bar is described as Structure II. There are certainly spectral characteristics shared between measure 72 and the earlier instances of Structure II at measure 9 and measure 17, but in this case, compact frequencies from the triangle, tambourine, and gong add an intensity absent from earlier incarnations (Figure 39). Carrying the sense of alternation even further, François describes measure 73 and measure 74 as the monophonic tutti of Structure III.

Rehearsal number 13, measure 75, marks what is widely agreed to be the conclusion of *Ionisation*. At this point, Chou and François agree that all of their textures and structures come together to end the piece. Here, Chou describes Texture I as predominant, and François considers Structure I to be combined with Structure III. The spectral picture is crowded (Figure 40). Instruments that define each texture or structure are visible, but the additional chaos created by the entrance of the piano, chimes, and celesta have a huge impact on the spectrum. Each pitched instrument is extremely dramatic, and it is difficult to explain the spectral finale in terms of the three textures and structures that have come before it. Measure 75 may initiate *Ionisation*'s conclusion, but it is also undoubtedly the climax of the piece. It is violent, dissonant, and unprecedented. The descriptions of textures and structures fail to express this.

It is not a coincidence that both Chou and François discuss the timbral content of *Ionisation* in terms of three different, but closely related templates. However, neither author's analysis accurately addresses the spectral reality of the piece. The discrepancies, many of which have been discussed here, stem from two sources. First, both analyses exhibit fundamental misunderstandings of the relationships
between certain instruments and their sonic profiles, as shown earlier in this study. Second, neither author provides sufficient description of their textures or structures, or how they are transformed over time. In regard to defining these timbral templates, François improves upon Chou's earlier work. While Chou relies heavily on instrument-based descriptions, François begins to base his definitions on timbre. Where François falls short is his limited understanding of the actual timbral content. If timbre is truly integral to the form of *Ionisation*, the “agent of delineation”, as has been suggested, then timbral considerations should guide both instrument groupings and formal organization on a larger scale. By defining and quantifying timbral characteristics, more accurate and testable analysis is possible.

Although he used it frequently, Chou intentionally avoided defining the word timbre. If instruments are to be organized according to timbres observed in spectral imaging, selective characteristics must be established. Foremost among these is a descriptive characteristic that has been used extensively thus far, compact/diffuse. According to Cogan,

> Compact/Diffuse refers to the width of each individual spectral element. Each spectral element can be either a compact partial strand, or a more diffuse, widely spread band of 'noise.' The designation *compact* indicates a spectrum formed of strands of partials, each reading out as a single frequency or pitch. The designation *diffuse* indicates a spectrum formed by bands covering more than one frequency or pitch (“noise” bands). The mixed designation *diffuse-compact* indicates a spectrum formed simultaneously of both strands and bands.\(^{33}\)

Compact/diffuse relationships are particularly important to *Ionisation* due to the number and complexity of instruments used. Generally speaking, compact instruments sound clearer, more pure, or even pitched. In the current context, highly compact instruments are rare and stand out significantly. By contrast, diffuse instruments do not have a clear pitch or tone. Most of the instruments in *Ionisation* are diffuse and blend together more readily than their compact counterparts.

No less important a timbral characteristic is range. Musicians typically define range by the highest and lowest notes that can be played on a given instrument. Percussion instruments present a

\(^{33}\) Cogan, 135.
unique challenge in this respect, particularly when it comes to highly diffuse spectral patterns. While few of the instruments in *Ionisation* play more than one pitch, they can excite wide swaths the frequency spectrum. Diffuse percussion instruments often fade gradually to silence at the high and low bordering frequencies of their ranges. While this can make determining precise ranges difficult, approximate ranges can still be observed. Sizes of ranges and high-low placement of ranges can be compared between instruments.

The final defining characteristics used in this study are attack and decay. Most percussion instruments demonstrate very clear attacks. Exceptions are noteworthy, but in this context, specific attack lengths are difficult to measure and of limited use. General patterns, however, are worth noting. Decay is much easier to see in spectral images. Although most instruments distinguish themselves through compact/diffuse properties and frequency range, instruments with broad, diffuse patterns are sometimes set apart by differences in decay. For example, the whip is a diffuse instrument with an unremarkable range, but its extremely short decay sets it apart from every other instrument in *Ionisation*.

For the most part, these properties have already been discussed for each individual instrument. Still, some perspective is useful. Figure 41 is a composite image that allows limited side by side comparison of ranges, attacks, and decays. Noise reduction has been applied to each example for the sake of clarity. However, due to this modification, compact/diffuse characteristics are best observed in the unaltered individual contextual spectral images presented in Figures 1 through 28.

Meanwhile, there are four general groups that make up the compact/diffuse spectrum. The first will be considered the Pure Compact group. These instruments present spectral images that are almost entirely defined by clear, compact bands. The second, slightly less concentrated group is Compact/Diffuse. Instruments in this group exhibit some clear, compact frequencies with an additional, significant, diffuse component either above, below, or superimposed over the compact frequencies. The third set of instruments are Diffuse with Core Sound. Instruments that are Diffuse
with Core Sound have a clear, relatively compact core sound, generally at the lower end of the instrument's range. A second, significant component of the sound is made up of a diffuse band that extends above, and possibly slightly below the core. The final category is made up of Pure Diffuse instruments. Pure Diffuse instruments produce a spectral image that has no compact component whatsoever. The instruments are classified as follows. Instruments are ordered by ascending pitch range.

1. Pure Compact
   Gong, Sirens, Chimes, Celesta, Sleigh Bells, Triangle, Anvil

2. Compact/Diffuse
   Cowbells, Tambourine

3. Diffuse with Core Sound
   Bass Drums, Snare Drum, Tambour Militaire, Tarole, Bongos, Tenor Drum, Claves, Castanets

4. Pure Diffuse
   Tam Tams, Piano, String Drum, Chinese Cymbal, Suspended Cymbal, Whip, Guiro, Woodblocks, Rim, Crash Cymbals, Maracas

Using these new instrument groups and defining characteristics, a new set of timbral templates akin to Chou and François' textures and structures can be created.

Template I (Figure 29) extends from measure 1 to measure 8. More than anything, it is defined by instruments with extremely long decay times. The upper and lower ends of the spectrum are populated by slow decay Pure Diffuse and Diffuse with Core Sound instruments. The middle of the spectrum features Pure Compact instruments with similarly long decay times. Additional attacks may be present, but they are not the defining features of the template. From a spectral standpoint, it is the steady-state combination of diffuse instruments on the fringes and compact bands in the middle are what make Template I stand out.

Template II (Figure 30) is first introduced from measure 9 to measure 12. Abandoning the long decay sounds of Template I, Template II focuses on lower range instruments that are Diffuse with Core Sound, and upper range Pure Diffuse and Diffuse with Core Sound instruments. Some low, diffuse
instruments have ranges that cover the middle of the spectrum without necessarily being centered there. Pure Compact and Compact/Diffuse instruments are not characteristic of Template II. Template I and Template II interact smoothly because of shared diffuse sound in the upper and lower registers. Short decay Diffuse with Core Sound instruments that fit soundly in Template II can be adapted to Template I by extending their decay times with drum rolls.

Template III is introduced midway through measure 18 (Figure 32). It is typically defined by low frequency Pure Diffuse and Diffuse with Core Sound timbres and mid to high frequency Compact/Diffuse and Pure Compact instruments. The highest Diffuse with Core Sound instruments may also substitute or complement the high frequency pure sonorities. The middle band from approximately 250 Hz – 1000 Hz is generally sparsely populated. Template III is related to Template I by virtue of the fact that the compact mid frequencies of Template I leave empty space that resembles Template III. Both templates are weighted to the outer ranges. However, Template III is more closely related to Template II, with the most obvious difference being the compact bands often present in the upper end of Template III. Smooth transitions from Template I to Template III can be accomplished by passage through Template II.

After returning to Template I in measure 13, Varèse moves to Template III midway though measure 18 by way of Template II. The diffuse material in the high and low bands from Template I are maintained leading into measure 17. Mid way through measure 18, the transition is completed by moving from the Diffuse with Core tambour militaire and tarole to the high Diffuse with Core castanets, the Compact/Diffuse tambourine and the Pure Compact sleigh bells. The range continuity and meshed diffuse and compact sonorities provide a clear sense of direction and meaning.

From measure 21, Template II and Template III alternate for several measures until Template I beings to assert itself at measure 30 (Figure 42). For a brief period from measure 30 to measure 38, all three templates are present (Figure 43). Once Template I drops out, Template II and Template III continue to alternate and blend up until measure 51.
The entrance of the anvil at measure 51 marks the first direct interplay between Template III and Template I. The Template III Pure Compact instruments in the upper register interact with the long decay, mid range, Pure Compact sonorities of Template I up until measure 56. At measure 56, the previous two templates trade off with the Diffuse with Core Sound snare sonorities of Template II for one measure. Once Template II has been heard, all three templates join together to drive toward the fermata before measure 66.

The alternations from measure 66 to measure 75 are generally clear (Figure 37). Measure 66 is primarily Template II with the slightest suggestion of Template III in the form of the Compact/Diffuse contribution of the tambourine. This is reinforced by the distinct presentation of Template III in the following measure, most clearly represented by the Pure Compact anvil on beats three and four. Measure 68 closely resembles measure 66. While both bars are heavily unison, the temptation to misinterpret the timbre must be resisted. The material is still comprised of low Diffuse with Core Sound sonorities. The increased dynamic level does not change this.

Measure 69 through measure 71 is not, however, a simple restatement of Template III (Figure 38). In short order, all three templates are present. The major drop off in activity at measure 72 is technically Template II and Template III, but that is not the intended function. As much as anything, the break is a breath; the calm before the storm. The unisons that follow are another example of loud Template II. In context, the tambourine is not enough to seriously enforce Template III.

As previously stated, the entrance of the piano at measure 75 is staggering (Figure 44). There is no warning. The heavy piano cluster fills the bottom end of the spectrum with especially dense, Pure Diffuse sound. While the piano is unprecedented, the immense sustain and low range identifies the entrance as Template I, the same timbral identification to begin the piece. In the following measures, the high Pure Compact sonority of the celesta and chimes evoke Template III. The intervening Diffuse with Core Sound snare attacks bring in Template II, completing the appearance of all three voices in the closing bars.
In my opinion, the concept of instrumental identity in Ionisation is carried to a point of extreme radicalization. Not only is there correlation between the envelopes, the speed of the rhythms, the phrase structure, the length of the phrases, and the meter in which they are inscribed, but there is also an associative relationship between the nature of the instrument and the origin to which it refers. The military drum, for example, fulfills its function in the totality of its identification: in the ears of the listener it plays a military march. The combination of bass drum and cymbals produces, as usual, strong downbeats; the maracas, castanets, and guiro do not hide their folklore origins. There are amusing references to Ravel's *Bolero*, and the anvil motive comes directly from *Das Rheingold*. The inclusion of the instruments producing realistic sounds from everyday life (sirens, whip, lion's roar) makes sense in view of the deliberate intent to use external referential elements as part of the internal form of the piece. This collection of instruments is a gathering of multiple voices which talk together, but do not really listen to each other, until suddenly they intone as a collective chorus. Varèse establishes here the cornerstone of concrete music; the concrete sound objects are welded into an abstract form that will completely transform their appearances. The "ions" come to us in a given state that cannot be modified, but the process of "ionisation" is precisely to transform them, nevertheless, into something more than what they were at the beginning. Therefore, in the performance of Ionisation, the referential characteristics of the instrumental identities should not be concealed; nor should they be accentuated, because this would destroy the abstract form that organizes their interactions and simultaneities. The superimposition of the sound objects produces a new, complex object, and it is this, the latter, that should emerge.\(^{34}\)

\(^{34}\) François, 61.
Ionisation is a complex object. While it is a wonderful thing to understand the rhythmic and motivic forces Varèse has brought to bear, it is the sound itself, the timbre that is at the heart of Ionisation.

Timbre is an elusive concept. Although Chou Wen-Chung and Jean Charles François recognized its absolute central importance to the work, neither theorist was able to get to the root of the issue. Both wrote excellent, enlightening analyses, but the central question “what is timbre?” defied them. In his conclusion, François responded,

Timbre is, in this case, that imperfect word that describes the sound in its entirety, in its all-including complexity, of which no separate parameters can be varied (or left out of consideration), without effecting some change in the overall characteristic of a particular sound.\(^{35}\)

To consider the timbre of an individual instrument, intuitive speculation is not good enough. It is not sufficient to look at the materials that constitute a piece of percussion equipment and declare its timbral function.

Using the groundbreaking techniques pioneered by Robert Cogan more than a quarter century ago, combined with modern technology, theorists can view sound for what it really is. The incredible complexity of timbre can be viewed, measured, and discussed one instrument at a time, or within the context of an entire piece of music. With the correct vocabulary, an understanding of Cogan's compact bands and diffuse noise, frequency ranges, length of decay, and the right equipment, spectral analysis can open a door to understanding the sound of music in a whole new way.

\(^{35}\) François, 77.