Stellar acoustics as input for music composition

Zoltán Kolláth
Konkoly Observatory
P.O.Box 67, H-1525 Budapest, Hungary
kollath@konkoly.hu
www.konkoly.hu/staff/kollath

Jenő Keuler
Institute for Musicology
P.O. Box 28, H-1250 Budapest, Hungary
keulerj@zti.hu

Abstract

Background in acoustics. *Variable stars* show light variations due to internal acoustic waves. There are strong physical mathematical parallels between stellar behaviour and musical instruments: the basic principles underlying their “overtone” frequencies are identical. However, “stellar instruments” have many characteristics that make their sounds different from ordinary musical instruments.
Background in theory/composition. Many composers have incorporated inharmonic spectra into their music. Computer technology now enables us to control inharmonic sound processes and deal with associated theoretical implications. Drawing stellar acoustics into the orbit of music fits in well with this trend in compositional practice.
Aims. Our main aim is to demonstrate that sounds designed according to the principles of stellar physics and the nature of the processes inside stars can be used as a new basis for music composition, theoretical reasoning, and aesthetic evaluation.
Main contribution. Both cosmic and musical events are determined by the temporal and hierarchical order of events, states and processes. Acoustic models of variable stars predict unusual patterns of “overtones” and variations in these patterns as the stars evolve. Due to the enormous size of stars, their oscillatory frequencies are orders of magnitudes lower than the audible range; therefore we should transpose those oscillations to the range of human hearing. However, the frequency range of possible stellar oscillations is much wider than the musical range, indicating a need for nesting points. These questions provide an interesting starting point for a cosmically inspired music theory. We developed a C-sound based computer application, to make the compositional experiments manageable.
Implications. In our research, we combine scientific and artistic approaches and ways of thinking. Astrophysicists can investigate the special modes of vibration in stars of diverse size and inner structure, present possible sound sets that “celestial instruments” might offer, and provide information on their acoustic spectra. Composers can then scrutinize the audible features of these sonances, their behavior in diverse musical contexts, their aptness for creating tonal tensions, and their suitability for creating expressive musical structures. These points are illustrated with reference to the authors’ *Stellar Music No. 1.*

Introduction

Natural processes and objects frequently provide models for musical sounds and composition. One can find plenty of examples among algorithmic compositions; we mention only one of them: the sonification of proteins (Dunn and Clark 1999). This experiment, like ours, is performed in a collaboration of a scientist and a musician. Oscillations of physical substances like crystals can be used for the generation of special sounds (Sethares 2005). The beauties of starry sky, the endless miracles of cosmos always inspired composers. The ensemble of crystal spheres used to model the planetary motion in Ptolemy's Cosmos was the first connection made between astronomy and music: the original concept of the "Music of the spheres" is credited to Pythagoras. Later, when Kepler found out that the motion of planets is not a combination of dozens of circular orbits, but single elliptical trajectories, he dropped the original idea of the music of the spheres. However, he found another miracle: the mathematical and physical simplicity of the planetary orbits, a new ideal harmony of the Universe. Contrary to previous ideas, when the planetary motion was the base for musical considerations, we use the interior physics of stars as a starting point. Furthermore, using computer models of stars and sound synthesis, stellar music can be composed with more physical and logical fidelity to the underlying relations. The adoption of stellar sounds to construct musical structures and to create musical composition poses only a restricted field of questions concerning music based on inharmonic spectra. A lot of compositions and theoretical publications are known in this wider sense of the problem; the most complete is Sethares' (2005) book. He tries to find a mathematical description for scales and consonance. His statements harmonise well with our former observations (Keuler 1997, 1999) but they are not related to our present compositional procedure strictly. Our purpose was, however, to bring about collaboration between scientific and artistic cognisance in our concrete research fields. Empirical experience, artistic considerations and theoretical questions arose in continuous interaction while we were creating the composition.

Stellar acoustics

Stars, like our Sun, are huge gaseous spheres. As in all material, in stellar interiors too, acoustic waves propagate. For a well defined group of stars there also exists a self excitation mechanism which is capable of generating steady standing waves inside distant suns. These waves are analogous to the waves inside organ pipes or other wind instruments. This group of stars is called the group of *pulsating variable stars*. However, there is no dense enough interstellar matter in which the stellar sounds could travel to Earth, *i.e.* there is no means of direct observation for these stellar waves. Yet, the brightness of these heavenly bodies is modulated due to the oscillations. Variable stars expand and contract in the course of wave motion. When the sphere contracts, its temperature increases and its brightness rises and when the star expands, its light intensity decreases again. This process makes it possible for earthlings to observe the acoustic waves of stars by measuring stellar light variations. The period of stellar oscillations extends from minutes to years, *e.g.* the range of frequencies is about 20 octaves wide compared to the 10 octave range of the audible sounds. Furthermore, even the highest pitch of the stars is approximately 15 octaves lower than normal A. It makes it necessary to transpose the stellar pulsation over a wide range to make them audible. The sounds of stars when transposed to perceptible frequencies, however, provide an interesting ensemble of *stellar (musical) instruments.*

The 20 octave wide register of stellar oscillations is valid only for the whole ensemble of stars. Individual stellar instruments have a narrow range of voice (usually a couple of octaves or even less). A star vibrates naturally only for a very short period compared to its lifetime (of course, it is long enough compared to human time scales). The pitch of stellar pulsations basically depends on the size of the star (like for real musical instruments) and on the density of its matter, too. The life of a star is determined by its birth mass, giving a variety of stellar destiny. During stellar evolution the stars expand and contract very slowly, providing very slow changes in their acoustic spectra. Interestingly enough, not only the periods of pulsations vary, but the pitch ratios in the overtone spectrum are shifting, too.

Contrary to most real musical instruments, the stellar spectra do not consist of harmonic pitches. The partial tones of stellar instruments are not in integer frequency relation to the fundamental oscillation, *i.e.* the overtones[1] are not harmonics, and it gives a significant difference to organ pipes. Indeed, similar effects also exist for cymbals and bells. We give some numerical examples of pitch intervals in the following section.

Examples of stellar instruments

In this section we present some examples of stellar musical instruments that we used for our experiments and for composition.

“Strange” model sequence

One of the main stellar instruments used in composition was based on a series of numerical models. While astronomers can observe only few selected partial tones in real stars, computer models of the stars give the full details of the spectrum. These invisible overtones are also integral parts of stellar acoustics, although no relative power or amplitude can be assigned to them. It gives some freedom to the composer while using the instrument. The temporal evolution of the sound can be freely modified by envelope curves, too.

Number of overtone	**I- standard root**		**II - Root one octave higher**	
	F/F_1	**Interval in cents**	**F/F_1**	**Interval in cents**
2	1.464	660	1.450	643
3	2.100	625	1.957	520
4	2.748	466	2.439	381
5	3.362	349	2.921	312
6	3.971	288	3.427	277
7	4.579	247	3.950	246
8	5.087	182	4.493	223
9	5.401	104	5.047	201
10	5.863	142	5.477	142
11	6.464	169	5.710	72
12	7.082	158	6.142	126
13	7.620	127	6.679	145

Table 1. The pitch relative to the fundamental and the previous partial tones for two different strange spectra. F/F0 gives the frequency compared to the fundamental sound. Case “I” is our standard strange spectrum. Shifting the fundamental (root) frequency by one octave higher the second (II) set is given. The intervals are given in cents relative to the previous overtone.

Table 1 gives the frequencies of the possible pitches of this stellar instrument together with the pitch displacements in cents[2] of the consecutive overtones for two different position of the root frequency. For harmonic spectra, the frequency ratio of the consecutive overtones monotonically decreases with the order of the overtone. However, there is a feature which distorts the frequency structure of the partial tones of the stars. For spectrum “I”, the intervals decrease until the ninth partial tone but then they increase for a few more partials.

Accidentally, the minimum interval in this sequence is close to a well tempered semitone. For spectrum "II", the minimum interval shifts to the 11th overtone and becomes narrower. The reason for this feature is that in addition to the normal overtones in the star, there is a so called *strange mode* overtone, too. As this strange mode moves through the spectrum with the evolving star, it produces the above mentioned variations in the partial tones. We note that by modelling stellar pulsations an unlimited variation of acoustic spectra can be gained – we have just selected one of our favourite sequences.

"Strange stellar bells"

For the previous instrument we used only the frequency information from the models, transients (attack, decay) were arbitrarily selected. In real acoustic musical instruments, there is a dissipation source, which makes the sound decay after the excitation ceased. Similar dissipation mechanism exists for stars, too. Then, the lifetime of oscillation is given by natural processes. The decay rates of different oscillation modes ("overtones") are different. This effect is ordinary for musical instruments, too (and the timbre changes during the release stage of the sound).

There is, however, a significant difference between stars and musical instruments: stellar acoustics allow not only for a decay but also for a self excitation of the oscillations. This mechanism works only in special groups of the stars, the ones that can be identified by their observable light variations.

Number of overtone	Relative decay time
1	195
2	1000
3	18.6
4	3.8
5	2.3
6	2.5
7	3.8
8	5.7
9	9.9
10	29.8
11	215
12	73.7
13	11.1
14	1.9

Table 2. Relative decay times in the strange stellar bell. The decay rate of the longest partial tone is set to 1000.

If all the modes are decaying, then in principle, no visible vibrations can be found. However, sudden events can happen during the stars' lifetimes that give a sharp attack to these sounds, like a clapper for the bell. Decay rates are taken from the models of the stars. With this additional information, a new group of virtual stellar instruments could be created with bell-like sounds. Note that the attack time is still a free parameter of the sound. The decay rates, corresponding to a strange stellar instrument, are listed in Table 2. The existence of a strange mode can be observed in the decay rates, since they increase in the neighbourhood (11th partial tone). This overtone dependence of the decay gives a special changing colour to the sound.

Stellar instruments based on real stars

As we mentioned before, some groups of stars have observable light variations due to a self excitation mechanism. There were observations for thousands of these kinds of stars. We selected a few representative ones for our experiments and compositions. Those are the following: *HR 1217* (Kurtz *et al.* 2002) and *HR 3831* (Baldry, Kurtz & Bedding 1998): In these stars magnetic field has a strong effect, producing splitting of the frequencies. The resulting close pitches cause interference *i.e.* amplitude modulation. In the case of *HR 1217*, partial tones are condensed in a very narrow frequency range. The highest pitch of the 8 main frequencies is only 7.1% higher than the lowest one. It means that 8 pitches are stuffed in an interval slightly larger than a semitone. Due to the splitting of the modes there are additional frequencies shifted up and down by 0.6 cents at each partials. Because of the dense spectrum, these stellar instruments have a fluctuating sound.

HR 3831 basically has a harmonic spectrum (it is not the result of harmonic overtones but of the distortion due to nonlinearity in the star). This spectrum is modulated by additional frequencies in a few cents' distance from the harmonic ones.

GD 358 (Kepler *et al.* 2003) is a white dwarf star. This type of stars is represented by a very dense frequency spectrum. Three dozens of individual frequency peaks are compressed into a one octave wide interval of the spectrum. However, there are partial tones three octaves lower and also in the higher frequency domain.

θ Tucanae (Paparó *et al.* 1996): This star is a member of the family of delta Scuti type stars. The number of observable partial tones for these stars ranges from a dozen to a few dozens. In the case of *θ* Tucanae 13 pulsation modes are determined. 10 of the frequencies are located in a 411 cent wide interval (a major third), while the remaining 3 ones sound 4-6 octaves lower.

Solar oscillation modes

The nearest star, our Sun does not have self excited modes; however the turbulent motion provides continuous energy for very small amplitude vibrations around 5 minutes of periodicity. Since the solar sound waves have very low energy levels, it only became possible to observe these oscillations during the last decades of the XXth century. Interestingly enough, with high precision measurements, the order of the number of observed solar pitches is a million! The song of our Sun sounds rather a colour noise than a chord. To acceptable sounds we selected groups of pitches on a physical ground. These stellar instruments are labelled with *SUN0*, *SUN1* and *SUN2* in our scores.

Chaotic oscillations

Although nonlinearity plays an important role in the sound generation mechanism of sustained-tone instruments, its effect is usually negligible in the acoustic resonator itself. On the contrary, for stars, the amplitude of the sound waves can be so high that nonlinear coupling of the modes occurs inside the wave propagating medium. This effect in the frequency spectrum of stellar can be observed by the presence of the harmonics of the modal frequencies and their sums and differences. (Note that the harmonic frequencies are not the results of the overtones but of the nonlinearities.) The nonlinearity of stellar oscillations together with the highly nonadiabatic nature of excitation mechanism can even result in chaotic vibrations of the star – these processes give additional colours to stellar voices.

Our experiments were based on two stars: *R Scuti* and *AC Herculis* (Buchler and Kolláth 2001). These two stars oscillate with long periods (30 and 70 days) and do not repeat their cycles exactly. Their variations look more or less erratic, but nonlinear, chaotic dynamics determines their cycles. Of the two stars, AC Herculis has more or less regular variations, while the sound of R Scuti is a coloured noise. We used not only the observations as wave samples but also the output of mathematical models, constructed from real light variations.

These models produce transitions from regular to chaotic vibrations. These sounds with increasing complexity are labelled with *AC3, AC4, AC5, AC6* and *AC* for AC Herculis and *RS6*, *RS6A* and *RSC* for R Scuti in the score.

"Stellar trumpet"

Stars are complex objects with nuclear energy production, complex processes in the propagation of electromagnetic radiation (from visible light to X-rays) coupled with hydrodynamics, etc. It indicates that stellar oscillations are also multifaceted states of suns. To understand a collection of effects involved in stellar pulsation, first we have to simplify our models. In the simplest model, only very small oscillations are assumed. Even in this case, the possible frequencies of stellar overtones are given very precisely. If motion is allowed only in the radial direction then our model is mathematically and physically analogous to the physics of organ pipes or wind instruments (Buchler *et al.* 1997). The possible frequencies of a wind instrument depend on the variation of its cross-section along its length. Mathematically the overtones are given by the Bernoulli-Webster equations. The simplified formalism of stellar pulsation can be converted to the Bernoulli-Webster equations. A similar acoustic analogy to a Schrödinger like equation is very well known in the study of wind instruments (Morse and Ingard 1968; Benade 1977). For stars, the spectrum of overtones is determined by the stellar structure. Based on the mathematical analogy, for a given star the cross section of an equivalent wind instrument, a "stellar trumpet" can be designed. We should emphasize that the analogy is not only a mathematical but also a physical one since acoustic waves are the same for both systems.

The major difference between the stellar trumpet and a real trumpet is the sound generation mechanism. While the valve mechanism of the lips is extremely important for the sound generation and the quality of sound in wind instruments, we use only the characteristics of the acoustic cavity (resonator) of the stellar trumpet. In stars the sound generation mechanism is located inside the cavity (due to interaction of the waves and the radiation of energy). This stellar trumpet is rather an idea than a musical instrument – we use its characteristic in several virtual instruments realized in our composition.

Stars and music theory

The task to compose music using stellar sounds and to score the "cosmic orchestra" results in many experiences and lessons to us. Of course, very much experience must be gathered to establish a special theory for this kind of music but the composer, in possession of his(her) professional knowledge, is capable of formulating preliminary theoretical considerations, at least questions. Let us see some of them:

Both cosmic and musical actions are determined by the succession of events, states and processes. While physical theories determine the possible temporal evolution of cosmic events, the scales for musical actions are limited by physiology and psychology of perception, sensation, cognition and experience.

The diverse kinds of stellar oscillations produce different types of sound. The first task of the composer is to find the possible musical functions the different types of stellar spectra can fill in. Are the discrete but inharmonic spectra suitable for forming tonal interrelations? How do the different types of noise-like but very characteristic spectra harmonise with each other or with other discrete spectra? What kinds of possibilities offer themselves to form shape and background contrasts? Where to place the two octave range stellar instruments into the eight-octave-wide range of music? How to organise pitch relations using a stellar instrument where the spectra of pitches are height dependent? To what extent is it practical to manipulate the frequency set of a spectrum? Can one find any way to utilise frequency relations of stellar spectra to organise rhythm or other time relations? Is it possible to make the objective time relations of stellar oscillations consistent with the human time thresholds of reception and with the elaboration of auditory information? How to deal with the stereophonic possibilities to create a “musical cosmos”? What kinds of possibilities do the different features of stellar sounds offer to induce “cosmic experiences”? Instead of listing questions and answers drawn from the authors’ work, we present a detailed analysis with note examples of our first composition entitled Stellar Music No. 1.

Stellar music No. 1

We have developed an alphanumeric score similar to C-sound score for our experiments. We also have made a special score consisting of two parallel planes (“staves”) to display the main structures of the music. The latter score is automatically produced from the alphanumeric score, and it is not capable OF itself to reconstruct the music. The upper “staff” indicates the spectral events and processes; the lower one shows the stereophonic occurrences. Time is shown in “minute:second” format along the horizontal axis for both “staves”. The frequency scale (vertical axis of the upper “staff”) is logarithmic (octaves). Stellar instruments are represented by symbols of their names: ¤ (grey): HR1217; × (light grey): HR3831; **Ø** (light grey): GD358; **$** (grey): cluster of 11-13th partial tones of the strange spectrum; **§** (light grey): **θ** Tucanae; **R** (grey): **RS6** – R Scuti; **R*** (grey): **RS6a** – variant of R Scuti; **S** (light grey): SUN0; **S*** (light grey): SUN2; ° (dark grey): stellar bell.

The lines without symbols represent the individual partial tones of the strange spectrum and the colour turns into grey for the sound with lower dynamics. The dynamic envelope of the sounds is indicated by the width of the lines. *Complex sounds* are denoted by the most important frequency (generally the lowest frequency) of the spectrum. Their frequency lines delineate the envelope of the whole sound, too. Other frequencies of the spectrum are shown only as short vertical lines at the beginning and at the end of the “notes”. The stereophonic locations of the sounds are represented along the vertical axis of the lower “staff”. The composition (in mp3 file) can be downloaded from our webpage: www.konkoly.hu/stellarmusic

Five sections characterise the global form of the composition: A, A_{var1}, B, C, and A_{var2}. Each section is exemplified by a sounding state based on a typical form of vibrations of a selected star. In addition to these main stellar oscillations, other kinds of variable star spectra emerge, too. Each section of the global form persists for about one minute. So much time was needed for a typical sound state to become exhausted, *i.e.* this period of time must elapse before a listener expects some new form of information. The actual length of the main sections deviates more or less from their nominal duration, because the speed (tempo) of the musical events changes on occasions. This relativistic course of time is grounded on musical reasoning. On the one hand, the events of musical happening should harmonise well with the natural rhythm of the acts of remembering and expectancy, to help a subjective (“undergoing”) strategy of perception. On the other hand, the structure of the events can be inspected clearly while the listener is using an objective (“observing”) strategy of perception. (Note that by “observing” strategy we mean the pictorial aspect of the music itself. In other words: we mean that sounds, sound connections and sound processes can appear as imaginary, “observable” formations in the course of perception.

As the spectra of the sounds are derived from stellar properties, the time durations used for the composition are also related to their inner relations. The values of durations are inversely proportional to the partial frequencies of the "*strange*" spectrum. Thus, they are in direct proportion to the periods of the oscillations. The values in seconds in our primary set (I) are the following: 30.00, 20.49, 14.28, 10.92, 8.92, 7.55, 6.55, 5.89, 5.55, 5.10, 4.64, 4.23, 3.93, 3.72 and 3.29. We also use a set (II) of shorter intervals: 10.00, 6.83, 4.76, 3.63 and 2.97 seconds. Sometimes the combination (sum or difference value) of the basic time values also appears.

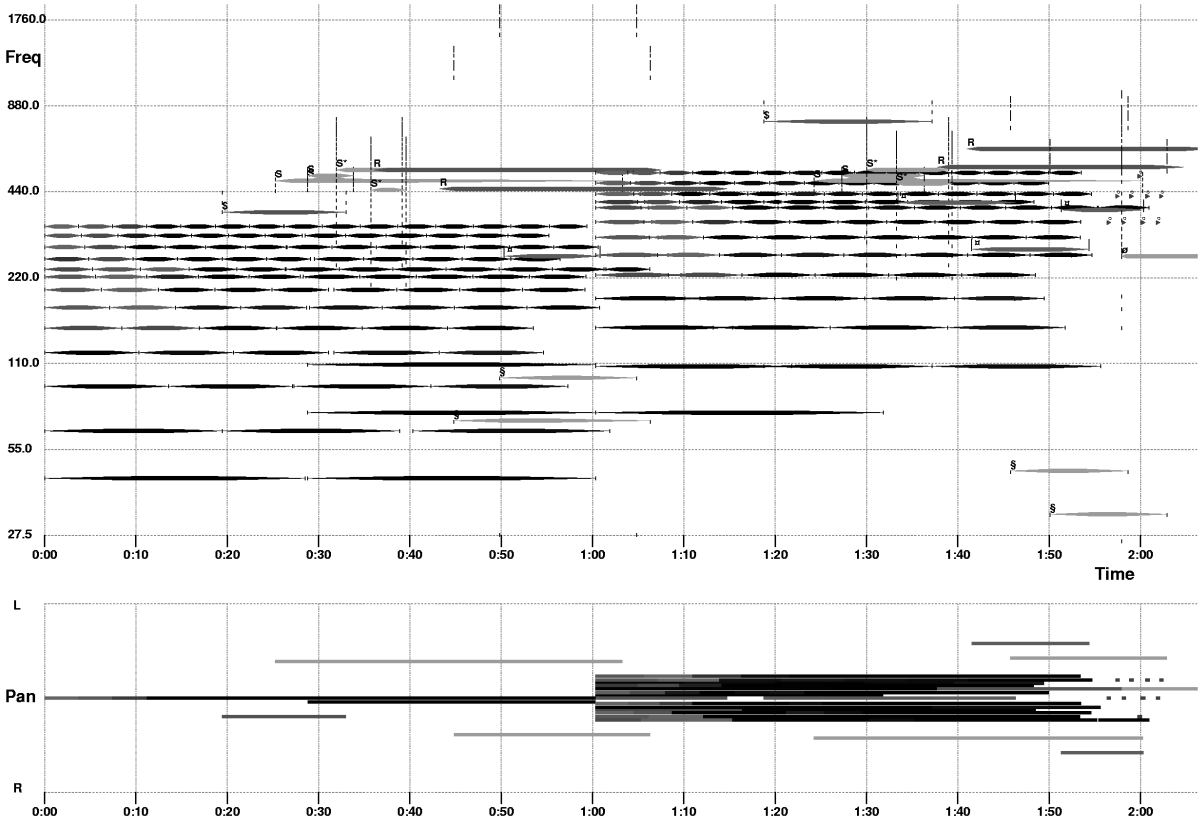

Figure 1. Score of the first two minutes (section “A” and “A_{var1}”) of “Stellar music No.1”

Section “A”: The sound material of the first section is determined by the strange stellar instrument. The pitch of its “root” (taking the lowest, fundamental frequency) is very low. It should be an F1 (we use a notation in that C4 means Middle C) and it seems to have an indefinite pitch in the sub adjacent octave. (See the lowest “note” in the score at the beginning of the composition~~1~~ — Fig. 1.) The uncertainty of the root pitch probably originates in a general impression of the spectrum.

The strange instrument is synthesised as ~~a~~ dynamic spectrum in the composition. The amplitudes of the partial tones keep growing and decreasing periodically in direct proportion to the period of the corresponding oscillations. The above-mentioned relation between the modulation time scale and the pitch of the partials is clearly visible in the score. The indefinite, low pitched sound material, with its sensual effect on the listener and the inner dynamics of the happening modeled after the slow infrasound trembling of the star have the task of touching the listener affectively right at the beginning of the composition. The sounding process appears in the middle of the stereophonic space quasi monophonically (you can only see a horizontal line in the lower “staff” of the score), nevertheless, the sounds fill in the whole space, because of their low frequencies. Later on, noise-like sounds are woven into the texture as well (*SUN0* — in the score = **S** light gray, *SUN2* **S*** light gray, *RS6* = **R** gray, *θ Tucanae* = **$** light gray. See them from time 0:26 on. - Fig. 1.) They take over the task of attracting attention by means of the gradual segregation of their timbres and by their continuously forming intensity levels. A relatively higher pitched cluster of sine tones, composed of the 11th-13th partial tones of the strange stellar instrument makes a continuous transition from the discrete spectrum of this instrument to the noise-like spectra of the new sounds to be definite (see at 0:19). The frequency ranges of these new sounds are higher, stronger and tighter than that of the strange stellar instrument. In addition to it, the chaotic one (*RS6* = **R** grey) has a rasping surface, thus the new sounds arrive easily at the foreground while the spectrum of the strange instrument falls into background. The appearance of new sounds is applied to produce increasing and decreasing musical tensions. Events of actions condense in the middle of the form section. The global timbre of sonority becomes brighter. Since the spectra of these later sounds derive from different stars of the Cosmos, they take place in diverse locations of the stereophonic space in the course of musical events. (See lower “staff” from time 0:26 on. - Fig. 1.). We note that their arrangement follows musical reasoning only. At the end of the section (at 0:51), a new type of stellar instruments appears with fluctuating amplitude (*HR 1217* = ¤ gray).

Section “$\mathbf{A}_{\mathbf{var1}}$” (Fig. 1.): The second section is a variation of the first one. Again, the most decisive sound material is the strange instrument. Being transposed a major sixth higher it takes back the task of attracting attention (note that only the “root tone” is transposed a major sixth higher, the other frequencies are adjusted to the transformed structure of the strange spectrum). The root of the spectrum is a D2, but its real pitch is ambiguous, it is nearly E*b*. The partial tones of the spectrum are rather scattered in the stereophonic space. It is important to irradiate the whole space of the “musical Universe” at this region of pitches[3]. (See lower “staff” from 0:59 on!). After the lapse of a few seconds noise-like stellar instruments take over the task of attracting attention again (see from 1:19 - Fig. 1.). Their heights do not vary too much but their placement in the stereophonic space turns round to the opposite direction. Only musical considerations give a reason for this turn. There are some changes in regard of the entrance order of different noise-like sounds, too. At the end of this section the fluctuating sound of *HR 1217* (= ¤ grey) can be heard from different places of the “firmament” (see at 1:35, 1:42 and 1:52). They rhyme well with the same sound-type heard at the end of section “A”, like cadenzas of the classic musical period.

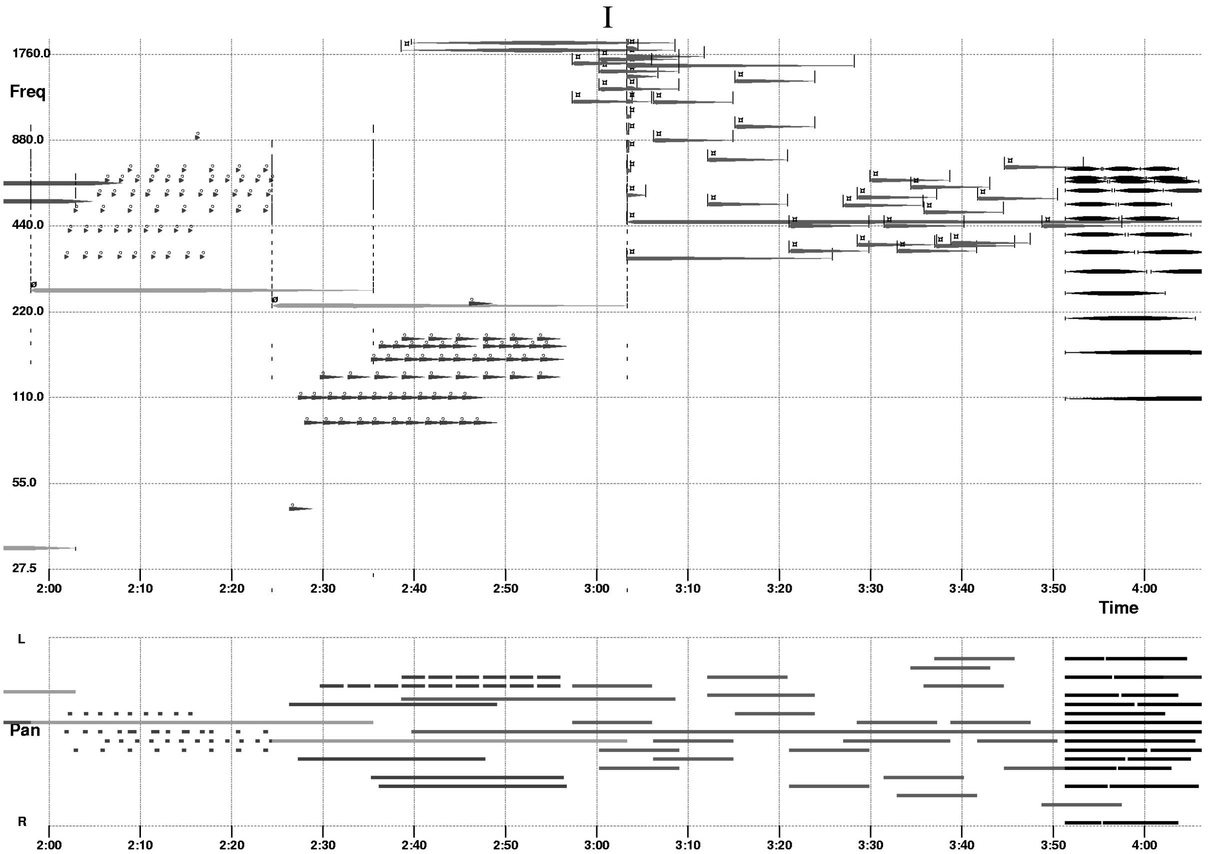

Figure 2. Score of the third and fourth minutes (section “B” and “C”) of “Stellar music No.1”

Section “B”. (Fig. 2.) Time is ripe for new musical thoughts. A new musical facture appears this time. While the first two sections (“A” and “A_{var1}”) were more favourable to a subjective (“undergoing”) strategy of perception, here the act is a sound picture suitable for “observing” in a “cosmic space” where sound events (sound objects) follow each other in a seemingly irregular succession. Now the musical happening takes place in the middle range of musical pitches contrary to the low pitches of the first two sections. Stellar bell instruments with their decay envelopes determine the sound texture of this section. They “glitter” at diverse places of the musical “firmament”. As a matter of fact, the apparent irregularity of the musical events is a result of the temporal and spatial relations of diverse regular succession of sounds. (Three values of time-duration are used here — 3.72, 3.29, and 2.97 seconds.) During the first part of this section (from 1:56 on), the spectra of the sounds are poor. Only the 9-11th partial tones of the stellar bell spectrum were used. Being synthesised in different transpositions (according to a frequency set of the strange spectrum) their series result~~s~~ in melody-like formations. However, they can also be regarded as “lights of diverse stars” with “diverse luminosity” because of their spatial scatter. The timbre becomes darker in the second part of the form section (from 2:26 on). Here the sounds are synthesised of twelve partial tones of the stellar bell spectrum. Melody like formations can also be heard in this part of the composition, but they are disarranged in consequence to the spatial scatter of sounds. In addition to the stellar bell, an important role is fulfilled by the noise like spectrum of *GD 358* (= **Ø** light grey). It functions as a pedal sound, first tuned a bit higher (at 1:58) while in the second half of this section it is transposed a bit lower (at 2:25). It has some other important tasks concerning the global form of the composition. It succeeds the series of coloured noises that had an important function in the previous sections. In a wider sense, it plays a role in the tonal organisation of the whole composition, because the rough pitches of its noise-like spectra can be contrasted to the root-like pitches of the previous two form sections (A and A_{var1}). In spite of the fact that the function of this form section is to make up a “well observable” sounding picture, means of *musical tension* exert their effect as well. The scale of musical phrasing becomes livelier. The spectral body of sounds in the 2nd part of the form section thickens compared to the 1st one, and a rise of *absolute pitch qualities* is also perceptible notwithstanding that the concrete pitches become deeper than they were in the 1st part of the section. A new material appears in the second half of section B, a new star “sparkles” with its high pitch: it is *HR 1217* (= ¤ grey). This sound appears at three different stereophonic places getting stronger and stronger (see from 2:38 on) as it anticipates the happening of the next section (at 2:57).

Section “C” (Fig. 2.). The musical process culminates here in the fourth form section. The sound state is determined by HR 1217 (= ¤ grey). This stellar instrument “glitters” on high frequencies in every region of the stereophonic space. The spectrum of this star is composed of interfering frequencies, which span a narrow region only. This property of the sound makes it possible to replace the sinusoidal waves of partial tones of other stellar instruments by the complex spectrum of *HR 1217*. This mixture of different virtual musical instruments has no physical origin but allows for some arbitrariness to the composer. To realise this idea, the heights of pitches and time-values of *HR 1217* were also adjusted to the frequency relations of the strange spectrum in order to preserve the organic coherence of the composition. At the same time, the decay rates of the frequency clusters were selected according to the properties of the stellar bell. The result is musically adequate to our idealized conception of the stellar trumpet.

The principal of the spatial placement of sounds is similar to that in the previous section but the left and the right side of the stereophonic space are adjusted according to the fact that here the “virtual root” is *C*, *F* respectively *F#*.[4] (The names of the pitches are nominal here and the real pitches differ from the nominal ones.) In this section, at the *golden section* of the composition, the idealised stellar trumpet rings out (at 3:04). The longest partial tone of its spectrum sounds until the end of the piece. It lasts for 115.76 sec~~,~~ while the duration of the other frequency components relates proportionally to this time value. This long lasting sound also confirms our choice of construction of the stellar trumpet – it would be very extraneous to its sound environment if it were synthesised by sine tones. The musical tension begins to release from the culmination due to the sinking range of pitches, but minor waves of tension-changes are also sensible in this period of the composition, owing to the changing density of events in the course of happening.

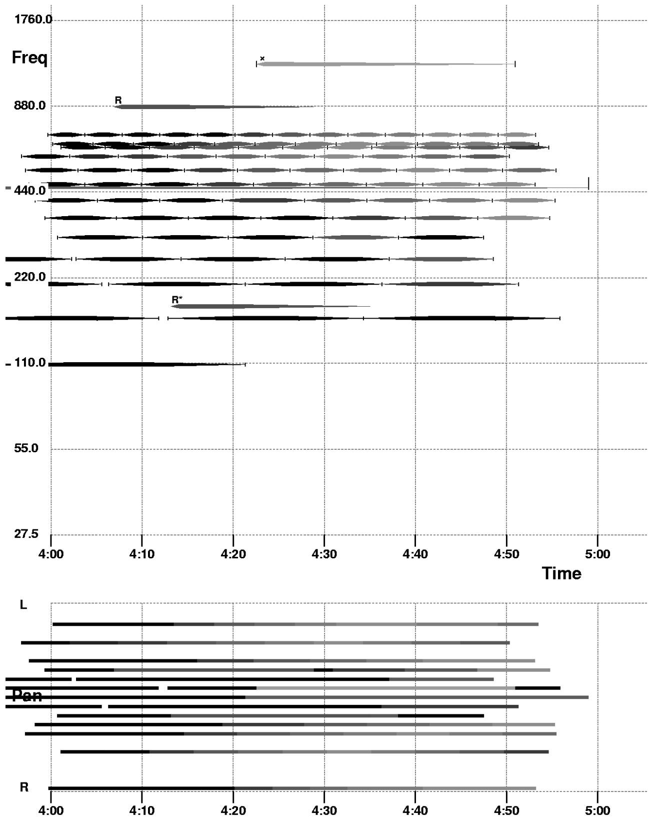

Figure 3. Score of the last minute (section "A_{var2}") of "Stellar music No.1"

Section "A_{var2}" (Fig 3.). In the closing section (from 3:51 on), the sound~~ing~~ state is determined by the dynamically stretching *strange* spectrum again. Its "root" is a deeply intoned *A2* pitch. (The nominal frequency is between *G#2* and *A2*.) Here, the diverse frequencies of the spectrum "irradiate" the whole stereophonic space (see lower "staff"). Thus, the infrasound oscillation of the *strange* spectrum becomes more perceptible. Contrary to the two opening sections of the composition, the main task is to prepare the musical process for completing the work here. Thus, the dynamic level of the whole sound material diminishes step by step (poco a poco decrescendo). Noise-like spectra (*RS6* = **R** grey, *RS6a* = **R*** grey) also emerge here (at 4:07 and 4:14). Near the end, a newer fluctuating star appears (*HR 3831* = **x** light grey — at 4:23). Finally, the tonal conclusion sounds as a deeply intoned *A2* and *Eb6*, as polar counterparts

With a global survey, tonalities at the beginning and the end of the composition approach the axis-like relation. (It is a terminus technicus in Hungarian music theory – proposed by Ernő Lendvai (Lendvai 1955, 1964) – for tones related as a minor third, major sixth and tritone to each other. In the composition a nominal F, a not quite clear D, and finally a higher intoned A*b*.) Concerning the global form of the composition, you find a developing part from the starting-point of the piece. The musical tension increases as far as the point of the golden section. From here on, the yarn of the happening unwinds to die away at the end of the composition.

Conclusion

If dealing with sounds of inharmonic spectra, the outcome of research in stellar acoustics can enrich the practice of musical composition. Stellar oscillations, being formed in lots of variation, offer an endless choice of possible musical adaptation. They can serve as models for sound phenomena, musical processes or compositional forms as well. Making use of the up-to-date computer technology and electro-acoustic instruments, the composer is capable of acquiring personal experiences about sound qualities derived from stellar oscillations transposed to the audible range of acoustic waves. He or she can typify and group the diverse kind of sounds. It is possible to keep trying and tasting the aesthetic effect of sounds, furthermore, it is possible to examine their interaction and common behavior in diverse musical contexts. The composer can weigh the suitability of different types of sounds regarding special musical functions. Applying stereophonic or quadraphonic system, the composer can create his/her little “musical cosmos”. Leaving the limited domain of stellar sounds he/she can try how sound phenomena of diverse origin can be combined with each other, and how they can get special semiotic functions in different musical contexts — should or should not they be traditional musical sounds.

The experiences of *our own experiments* proved it unambiguously that stellar oscillation provides suitable input for music composition. A large number of stellar sounds can be judged as aesthetic phenomena by themselves. Embedded in some convenient context, even nasty sounds can fulfill artistic musical roles. The formal variety of the sounds makes it possible to create differentiated musical textures and to form musical processes of different character. We found ways and means to produce musical tensions and relaxation. Regarding the assortment offered by sound phenomena of diverse timbre, saturation, inner dynamic, the composer surely can find the very type of sound for the desirable musical function in a given situation. In special cases one can alter the sound spectrum, too. Omitting some frequencies from the spectrum the timbre can be modified without altering the basic character of the sound. In spite of the fact that pitches of stellar sounds can usually be defined merely as approximations and sometimes even the seemingly well defined pitches diverge from the nominal values, a tonality in a wider sense can be created by this kind of sounds. Tonal centers or axes can segregate from other sounds, which are extraneous to them.

The oscillation of stars can become a model not only for sound phenomena but for actions in a happening as well. According to our experiences, the seemingly "irrational time relations" to be found between the partial frequencies of the "strange" spectrum can have an aesthetic impression inside time quanta of 2–3 seconds. Moreover, time relations of larger scale can also be reconcilable with natural musical sense. The composer need not plan his/her piece in a speculative way when using some stellar model for the longer sections of the composition. An intuitively fixed dividing point can probably be rounded up to a closer time point preferred by the stellar model, afterwards.

A co-operation among musicians and stellar astrophysicists can be profitable. The sound examples of stellar processes have already been in use in public relation activities. An astronomer interested in music can search for newer and newer interesting type of stellar sounds. The idea of stellar instruments can encourage experimentation on planning new acoustic instruments. Resemblance between distant scientific fields can come to light in a maintained collaboration.

Acknowledgements. The authors thank to István Pintér, who introduced them to each other initiating this collaboration of different fields. This work was supported by the Hungarian OTKA grant T-038441.

References

Baldry, I. K.; Kurtz, D. W., & Bedding, T. R. (1998). Confirmation of the oblique pulsator model for the rapidly oscillating AP star HR 3831. *Monthly Notices of the Royal Astronomical Society*, *300*, L39-42.

Benade, A. H. (1977), On plane and spherical waves in horns with non-uniform flare. In E.L. Kent (Ed) *Musical acoustics: Piano and wind instruments* (p 110). Stroudsburg, PA: Dowden,Hutchinson & Ross.

Buchler, J. R., Yecko, P. A., & Kolláth, Z. (1997). The nature of strange modes in classical variable stars. *Astronomy & Astrophysics*, *326*, 669-681.

Buchler, J.R. & Kolláth, Z. (2001). Nonlinear analysis of irregular variables. In: M. Takeuti and D. D. Sasselov (Eds) *Stellar pulsation - nonlinear studies, Astrophysics and space science library, 257*, pp. 185-213. Dordrecht: Kluwer Academic Publishers.

Dunn, J. & Clark, M.A. (1999). Life music: The sonification of proteins. *Leonardo, 32*, 25-32.

Keuler, J. (1997). Problems of shape and background in sounds with inharmonic spectra. In *Music, gestalt, and computing.* pp. 214-224. + CD. Ed. Marc Leman. Berlin, Heidelberg, New York etc. etc. Springer Verlag.

Keuler, J. (1999). The paradoxes of octave identities. In *Studia Musicologica Academiae Scientiarum Hungaricae.* pp 211-224. Ed. József Ujfalussy. Budapest. Akadémiai Kiadó

Kepler, S. O., Nather, R. E., Winget, D. E. et al. (2003). The ever-changing pulsating white dwarf GD358. *Astronomy and Astrophysics*, *401*, 639-654.

Kurtz, D. W., Kawaler, S. D. & Riddle, R. L. (2002). Discovery of the 'missing' mode in HR 1217 by the Whole Earth Telescope. Monthly *Notices of the Royal Astronomical Society, 330*, L57-61.

Lendvai, E. (1955). *Bartók stílusa* [Batók's style]. Budapest, Zeneműkiadó

Lendvai, E. (1964). *Duality and synthesis in the works of B. Bartók*. New York (London 1967)

Marks, L. E. (1984) Synesthesia and the arts. In *Cognitive processes in the perception of art*. pp. 427-447. Eds. Crozier, W. R. & Chapman, A. J. — Elsevier Science Publishers B. V. North-Hooland.

Morse, P.M. & Ingard, K.U., (1968), *Theoretical acoustics*. McGraw-Hill: New York

Paparó, M., Sterken, C., Spoon, H. W. W. & Birch, P. V. (1996). Complex behaviour of the δ Scuti star θ Tucanae. I. Frequencies in the light variation. *Astronomy and Astrophysics*, *315*, 400-410.

Sethares, William A. (2005 second edition). *Tuning, timbre, spectrum, scale.* Berlin: Springer.

---

[1] In the astronomical jargon the word "overtone" is used for the modes of oscillations independently whether their spectrum is harmonic or not. In the musical literature, however, overtone usually means only harmonic.

[2] We use the relative cent scale to give frequency ratios. A semitone is given by 100 cents and the octave interval equals to 1200 cents.

[3] NB. When we use metaphors, such as "musical cosmos", "lights of stars", "illumine the whole musical space" etc.; we endeavour to give a more precise, pictorial description of the musical structures as they develop in the stereophonic space. Consider this as an analysis of

---

the pictorial aspect of the musical happening. Our metaphors are based on a well-known synesthetic connection between pitch and brightness. See e.g. Marks 1984, p 443/444.

[4] The equal-tempered twelve-tone scale served as a system for orientation in our experiments. We generally put the quasi “root tones” of stellar scales in different places in the tempered twelve-tone system. In the sentence, referred to in this note, the expression “virtual root” does not mean root tone of HR1217. On the contrary! “Root tones” of scales based on the strange spectrum are attached to three different tones of the tempered system. The pitches of spectra, based on HR1217, are placed at different frequencies of the stellar scales.