

Genome sequence of the soil bacterium *Saccharomonospora azurea* type strain (NA-128^T)

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Keywords

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Abstract

Saccharomonospora azurea Runmao *et al.* 1987 is a member to the genomically so far poorly characterized genus *Saccharomonospora* in the family *Pseudonocardiaceae*. Members of the genus *Saccharomonosporas* are of interest because they originate from diverse habitats, such as leaf litter, manure, compost, surface of peat, moist and over-heated grain, where they might play a role in the primary degradation of plant material by attacking hemicellulose. They are Gram-negative staining organisms classified among the usually Gram-positive actinomycetes. Next to *S. viridis*, *S. azurea* is only the second member in the genus *Saccharomonospora* for which a completely sequenced type strain genome will be published. Here we describe the features of this organism, together with the complete genome sequence with project status ‘permanent draft’, and annotation. The 4,763,832 bp long chromosome with its 4,472 protein-coding and 58 RNA genes was sequenced as part of the DOE funded Community Sequencing Program (CSP) 2010 at the Joint Genome Institute (JGI).

Introduction

Strain NA-128^T (= DSM 44631 = ATCC 43670 = NBRC 14651) is the type strain of the species *Saccharomonospora azurea* [1], one out of currently nine members in the genus *Saccharomonospora* [51]. The strain was originally isolated in the course of screening for new antibiotics from a soil sample collected near Guangyun City, Sichuan (China) [1]. The genus name *Saccharomonospora* was derived from the Greek words for *sakchâr*, sugar, *monos*, single or solitary, and *spora* a seed or spore, meaning the sugar (-containing) single-spored (organism) [5]; the species epithet was derived from the Latin adjectiv *azurea*, azure, referring to the color of the areal mycelium [1]. Yoon *et al.* [2] showed in 1999 *via* DNA-DNA hybridization that ‘*S. caesia*’ [3] (formerly known as ‘*Micropolyspora caesia*’ [4]), which was neglected from the approved list [20], was indeed a synonym of *S. azurea*. *S. azurea* and the other type strains of the genus *Saccharomonospora* were selected for genome sequencing in a DOE Community Sequencing Project (CSP 312) at Joint Genome Institute

(JGI), because members of the genus (which originate from diverse habitats, such as leaf litter, manure, compost, surface of peat, moist and over-heated grain) might play a role in the primary degradation of plant material by attacking hemicellulose. This expectation was underpinned by the results of the analysis of the genome of *S. viridis* [16], one of the recently sequenced GEBA genomes [46]. The *S. viridis* genome, so far the sole sequenced genome from the genus *Saccharomonospora*, contained an unusually large number (24) of genes for glycosyl hydrolases (GH) belonging to 14 GH families, which were identified in the Carbon Active Enzyme Database [47]. Hydrolysis of cellulose and starch were also reported for other members of the genus (that are included in CSP 312), such as *S. marina*, *S. halophila*, *S. saliphila*, *S. paurometabolica*, and *S. xinjiangensis* (see original descriptions of the type strains in *IJSEM*). Here we present a summary classification and a set of features for *S. azurea* AN-128^T, together with the description of the genomic sequencing and annotation.

Classification and features

A representative genomic 16S rRNA sequence of *S. azurea* NA-128^T was compared using NCBI BLAST [9,10] under default settings (e.g., considering only the high-scoring segment pairs (HSPs) from the best 250 hits) with the most recent release of the Greengenes database [11] and the relative frequencies of taxa and keywords (reduced to their stem [12]) were determined, weighted by BLAST scores. The most frequently occurring genera were *Saccharomonospora* (47.9%), *Kocuria* (17.7%), *Corynebacterium* (9.4%), *Kibdelosporangium* (6.0%) and *Prauserella* (5.5%) (176 hits in total). Regarding the eight hits to sequences from members of the species, the average identity within HSPs was 99.5%, whereas the average coverage by HSPs was 99.8%. Regarding the 42 hits to sequences from other members of the genus, the average identity within HSPs was 97.0%, whereas the average coverage by HSPs was 98.3%. Among all other species, the one yielding the highest score was *Saccharomonospora xinjiangensis* (AJ306300), which corresponded to an identity of 98.9% and an HSP coverage of 100.1%. (Note that the Greengenes database uses the INSDC (= EMBL/NCBI/DDBJ) annotation, which is not an authoritative source for nomenclature or classification.) The highest-scoring environmental sequence was FN667533 ('stages composting process pilot scale municipal drum compost clone PS3734'), which showed an identity of 100.0% and an HSP coverage of 97.9%. The most frequently occurring keywords within the labels of all environmental samples which yielded hits were 'feedlot' (7.9%), 'top' (4.1%), 'beef, cattl, coli, escherichia, habitat, marc, neg, pen, primari, secondari, stec, surfac, synecolog' (3.9%), 'feedbunk' (2.3%) and 'compost' (1.7%) (74 hits in total). Environmental samples which yielded hits of a higher score than the highest scoring species were not found.

Figure 1 shows the phylogenetic neighborhood of *S. azurea* in a 16S rRNA based tree. The sequences of the three identical 16S rRNA gene copies in the genome do not differ from the previously published 16S rRNA sequence (Z38017).

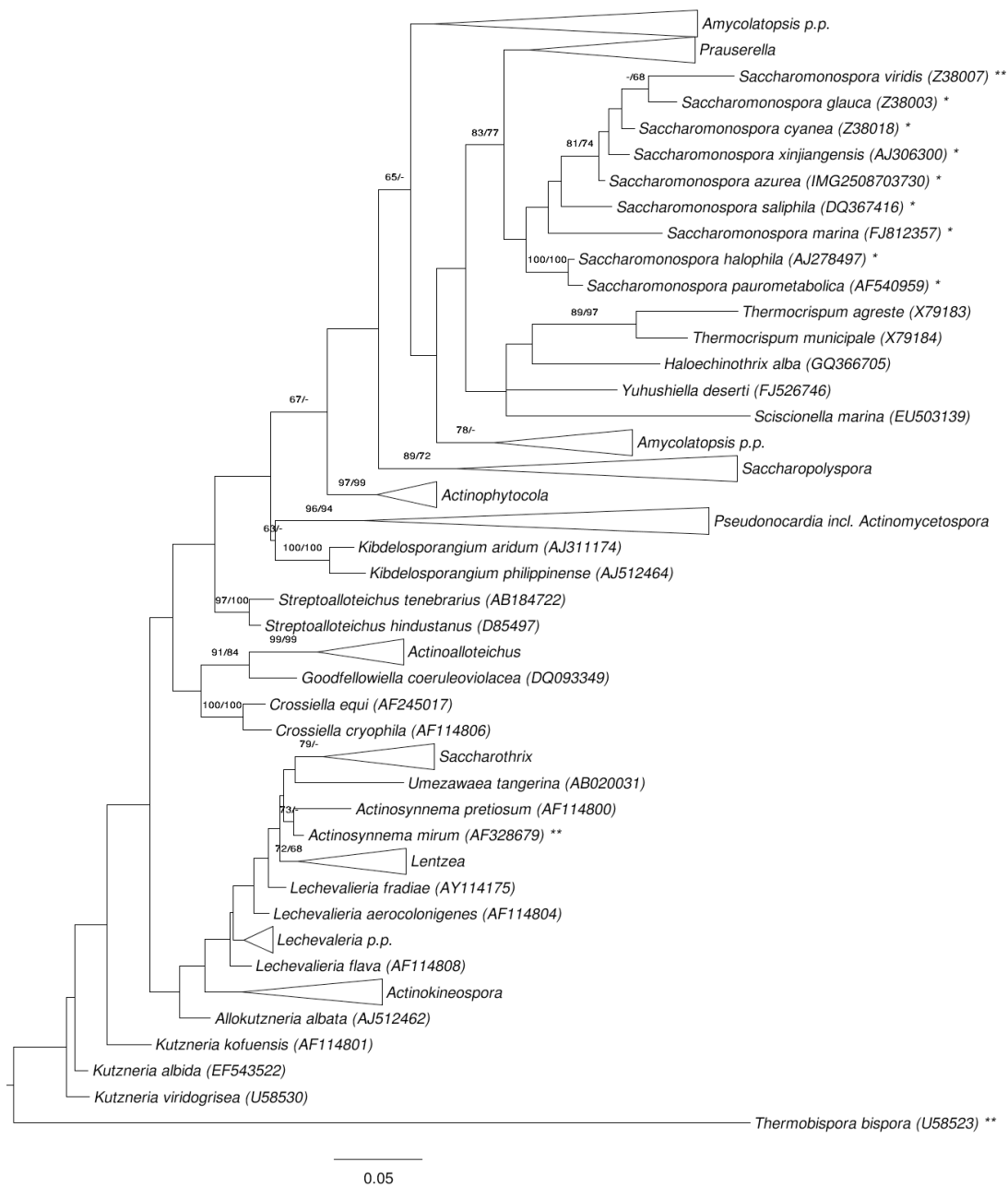


Figure 1. Phylogenetic tree highlighting the position of *S. azurea* relative to the type strains of the other species within the family *Pseudonocardiaceae*. The tree was inferred from 1,386 aligned characters [13,14] of the 16S rRNA gene sequence under the maximum likelihood (ML) criterion [15]. Rooting was done initially using the midpoint method [8] and then checked for its agreement with the current classification (Table 1). The branches are scaled in terms of the expected number of substitutions per site. Numbers adjacent to the branches are support values from 550 ML bootstrap replicates [17] (left) and from 1,000 maximum-parsimony bootstrap replicates [18] (right) if larger than 60%. Lineages with type strain genome sequencing projects registered in GOLD [19] are labeled with one asterisk, those also listed as 'Complete and Published' with two asterisks [16,48,49]. *Actinopolyspora iraqiensis* Ruan *et al.* 1994 was ignored in the tree, because a proposal for the transfer of this species to the genus *Saccharomonospora* [6] was recently rejected on formal criteria [5].

Cells of *S. azurea* NA-128^T stain Gram-negative and form an irregularly branched vegetative mycelium of 0.3 to 0.4 μm diameter (Figure 2) [1]. The monopodally branching aerial

mycelium has a diameter of 0.3 to 0.6 μm [1]; the mature mycelium and the spores are azure to cyaneus when grown on Oatmeal agar (ISP3) or on Czapek sucrose agar [1]. Smooth, round spores are 0.8 to 1.0 μm long, mostly found on the aerial mycelium, but rarely on the substrate mycelium [1]. No distinct soluble pigment was detectable [1]. The growth range of strain NA-128^T spans from 24-40°C, with an optimum at 28-37°C [1]. Strain NA-128^T grows well in up to 7% NaCl containing medium, but is inhibited at 10% NaCl [1]. Physiological characteristics such as growth substrates, gelatin formation and peptonization of milk are described in detail by Runmao (1987) [1].

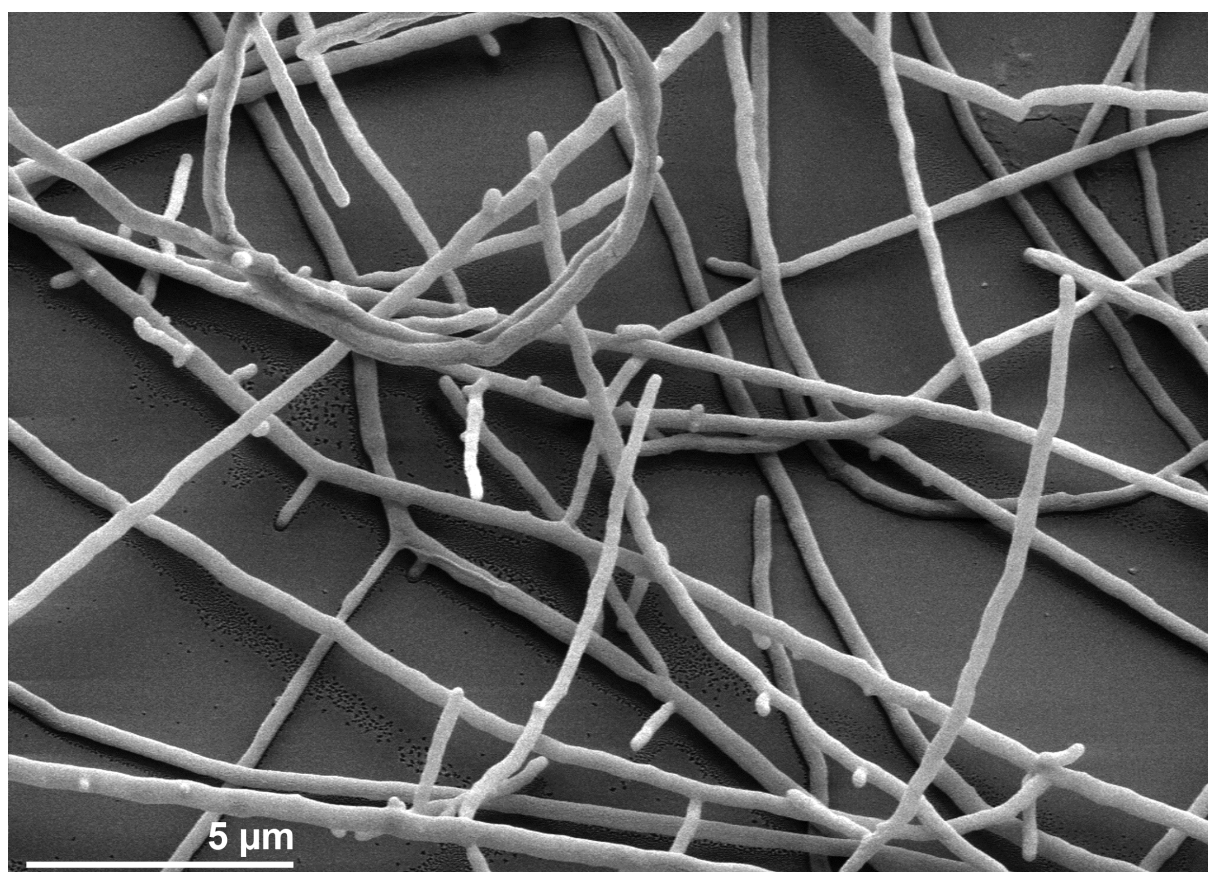


Figure 2. Scanning electron micrograph of *S. azurea* AN-128^T

Chemotaxonomy

The cell wall of strain AN-128^T contains *meso*-diaminopimelic acid; Galactose and arabinose are present, indicating a type IV cell wall / type A whole cell sugar pattern [1]. The fatty acids spectrum is dominated by almost 80% hexadecanoic acids: *iso*-C_{16:0} (27.0%), C_{16:1 cis-9} (17.0%), *iso*-C_{16:0 2-OH} (14.0%), C_{16:0} (palmitic acid, 13.0%), *iso*-C_{16:1 H} (7.0%), *anteiso*-C_{16:0} (1.0%) [50]. There are no data available for polar lipids and quinines of this strain.

Table 1. Classification and general features of *S. azurea* AN-128^T in accordance with the MIGS recommendations [7].

| MIGS ID | Property | Term | Evidence code |
|---------|------------------------|----------------------------------|-------------------|
| | Current classification | Domain <i>Bacteria</i> | TAS [21] |
| | | Phylum <i>Actinobacteria</i> | TAS [45] |
| | | Class <i>Actinobacteria</i> | TAS [24] |
| | | Subclass <i>Actinobacteridae</i> | TAS [24,44] |
| | | Order <i>Actinomycetales</i> | TAS [20,24,43,44] |
| | | Suborder <i>Pseudonocardinae</i> | TAS [25,26,44] |

| | | | |
|-----------|------------------------|---|----------------|
| | Family | <i>Pseudonocardiaceae</i> | TAS [22-25,44] |
| | Genus | <i>Saccharomonospora</i> | TAS [20,26] |
| | Species | <i>Saccharomonospora azurea</i> | TAS [1] |
| | Type-strain | AN-128 | TAS [1] |
| | Gram stain | negative | NAS |
| | Cell shape | variable | NAS |
| | Motility | non-motile | NAS |
| | Sporulation | single spores with smooth surface, mainly on aerial mycelium | TAS [1] |
| | Temperature range | mesophile, 24–40°C | TAS [1] |
| | Optimum temperature | 28–37°C | TAS [1] |
| | Salinity | grows in up to 7% NaCl; 10% is inhibitory | TAS [1] |
| MIGS-22 | Oxygen requirement | aerobic | TAS [1] |
| | Carbon source | mono, di- and trisaccharides | TAS [1] |
| | Energy metabolism | chemoheterotrophic | NAS |
| MIGS-6 | Habitat | soil | TAS [1] |
| MIGS-15 | Biotic relationship | free living | NAS |
| MIGS-14 | Pathogenicity | none | NAS |
| | Biosafety level | 1 | TAS [27] |
| MIGS-23.1 | Isolation | soil | TAS [1] |
| MIGS-4 | Geographic location | Guangyuan City, Sichuan (China) | TAS [1] |
| MIGS-5 | Sample collection time | 1986 or before | NAS |
| MIGS-4.1 | Latitude – Longitude | 32.45 – 105.84 | NAS |
| MIGS-4.2 | | | |
| MIGS-4.3 | Depth | not reported | |
| MIGS-4.4 | Altitude | not reported | |

Evidence codes - TAS: Traceable Author Statement (i.e., a direct report exists in the literature); NAS: Non-traceable Author Statement (i.e., not directly observed for the living, isolated sample, but based on a generally accepted property for the species, or anecdotal evidence). These evidence codes are from of the Gene Ontology project [28].

Genome sequencing and annotation

Genome project history

This organism was selected for sequencing as part of the DOE Joint Genome Institute Community Sequencing Program (CSP) 2011, CSP 312, “Whole genome type strain sequences of the genus *Saccharomonospora* – a taxonomically troubled genus with bioenergetic potential”. The genome project is deposited in the Genomes On Line Database [19] and the complete genome sequence is deposited in GenBank. Sequencing, finishing and annotation were performed by the DOE Joint Genome Institute (JGI). A summary of the project information is shown in Table 2.

Table 2. Genome sequencing project information

| MIGS ID | Property | Term |
|---------|----------------------|--|
| MIGS-31 | Finishing quality | Improved high quality draft |
| MIGS-28 | Libraries used | Three genomic libraries: one 454 pyrosequence standard library, one 454 PE library (12 kb insert size), one Illumina library |
| MIGS-29 | Sequencing platforms | Illumina GAii, 454 GS FLX Titanium |

| | | |
|-----------|----------------------------|--|
| MIGS-31.2 | Sequencing coverage | 1,025.0 × Illumina; 8.6 × pyrosequence |
| MIGS-30 | Assemblers | Newbler version 2.3, Velvet version 1.0.13, phrap version SPS - 4.24 |
| MIGS-32 | Gene calling method | Prodigal |
| | INSDC ID | <i>not yet available</i> |
| | GenBank Date of Release | <i>not yet</i> |
| | GOLD ID | Gi07579 |
| | NCBI project ID | 62037 |
| | Database: IMG | 2508501044 |
| MIGS-13 | Source material identifier | DSM 44631 |
| | Project relevance | Bioenergy and phylogenetic diversity |

Strain history

The history of strain NA-128^T starts in 1985 with Hu Runmao (Sichuan Industrial Institute of Antibiotics, People's Republic of China) who deposited the strain in the American Type Culture Collection (accession ATCC 43670), from where it was later deposited in the German Collection of Microorganisms and Cell Cultures (accession DSM 44631), where cultures of the strain are maintained freeze dried as well as in liquid nitrogen.

Growth conditions and DNA isolation

Strain NA-128^T, DSM 44631, was grown in DSMZ medium 83 (Czapek Peptone Medium) [41] at 28°C. DNA was isolated from 0.5-1 g of cell paste using Jetflex Genomic DNA Purification Kit (GENOMED 600100) following the standard protocol as recommended by the manufacturer with the following modifications: extended cell lysis time (60 min.) with additional 30µl Achromopeptidase, Lysostaphin, Mutanolysin; proteinase K was applied in 6-fold the supplier recommended amount for 60 min. at 58°C. The purity, quality and size of the bulk gDNA preparation were assessed by JGI according to DOE-JGI guidelines. DNA is available through the DNA Bank Network [42].

Genome sequencing and assembly

The genome was sequenced using a combination of Illumina and 454 sequencing platforms. All general aspects of library construction and sequencing can be found at the JGI website [29]. Pyrosequencing reads were assembled using the Newbler assembler (Roche). The initial Newbler assembly consisting of 215 contigs in one scaffold was converted into a phrap [30] assembly by making fake reads from the consensus, to collect the read pairs in the 454 paired end library. Illumina GAii sequencing data (5,162.6 Mb) was assembled with Velvet [31] and the consensus sequences were shredded into 1.5 kb overlapped fake reads and assembled together with the 454 data. The 454 draft assembly was based on 80.3 Mb 454 draft data and all of the 454 paired end data. Newbler parameters are -consed -a 50 -l 350 -g -m -ml 20. The Phred/Phrap/Consed software package [30] was used for sequence assembly and quality assessment in the subsequent finishing process. After the shotgun stage, reads were assembled with parallel phrap (High Performance Software, LLC). Possible mis-assemblies were corrected with gapResolution [29], Dupfinisher [39], or sequencing cloned bridging PCR fragments with subcloning. Gaps between contigs were closed by editing in Consed, by PCR and by Bubble PCR primer walks (J.-F. Chang, unpublished). A total of 158 additional reactions were necessary to close gaps and to raise the quality of the finished sequence. Illumina reads were also used to correct potential base errors and increase consensus quality using a software Polisher developed at JGI [40]. The error rate of the completed genome sequence is less than 1 in 100,000. Together, the combination of the Illumina and 454 sequencing platforms provided 1,033.6 x coverage of the genome. The final assembly contained 345,324 pyrosequence and 64,928,268 Illumina reads.

Genome annotation

Genes were identified using Prodigal [32] as part of the Oak Ridge National Laboratory genome annotation pipeline, followed by a round of manual curation using the JGI GenePRIMP pipeline [33]. The predicted CDSs were translated and used to search the National Center for Biotechnology Information (NCBI) non-redundant database, UniProt, TIGRFam, Pfam, PRIAM, KEGG, COG, and InterPro databases. These data sources were combined to assert a product description for each predicted protein. Non-coding genes and miscellaneous features were predicted using tRNAscan-SE [34], RNAMMer [35], Rfam [36], TMHMM [37], and signalP [38].

Genome properties

The genome consists of a 4,763,852 bp long chromosome a 70.1% G+C content (Table 3 and Figure 3). Of the 4,530 genes predicted, 4,472 were protein-coding genes, and 58 RNAs; 96 pseudogenes were also identified. The majority of the protein-coding genes (73.8%) were assigned a putative function while the remaining ones were annotated as hypothetical proteins. The distribution of genes into COGs functional categories is presented in Table 4.

Table 3. Genome Statistics

| Attribute | Value | % of Total |
|---|-----------|------------|
| Genome size (bp) | 4,763,852 | 100.00% |
| DNA coding region (bp) | 4,287,642 | 90.00% |
| DNA G+C content (bp) | 3,331,901 | 70.08% |
| Number of replicons | 1 | |
| Extrachromosomal elements | 0 | |
| Total genes | 4,530 | 100.00% |
| RNA genes | 58 | 1.28% |
| rRNA operons | 3 | |
| tRNA genes | 47 | 1.04% |
| Protein-coding genes | 4,472 | 98.72% |
| Pseudo genes | 96 | 2.12% |
| Genes with function prediction (proteins) | 3,342 | 73.77% |
| Genes in paralog clusters | 2,354 | 51.96% |
| Genes assigned to COGs | 3,312 | 73.11% |
| Genes assigned Pfam domains | 3,450 | 76.16% |
| Genes with signal peptides | 1,332 | 29.40% |
| Genes with transmembrane helices | 1,070 | 23.62% |
| CRISPR repeats | 0 | |

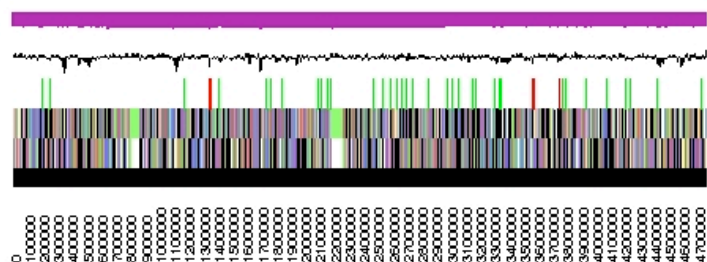


Figure 3. Graphical map of the chromosome. From bottom to the top: Genes on forward strand (color by COG categories), Genes on reverse strand (color by COG categories), RNA genes (tRNAs green, rRNAs red, other RNAs black), GC content, GC skew.

Table 4. Number of genes associated with the general COG functional categories

| Code | value | %age | Description |
|------|-------|------|--|
| J | 171 | 4.6 | Translation, ribosomal structure and biogenesis |
| A | 1 | 0.0 | RNA processing and modification |
| K | 394 | 10.6 | Transcription |
| L | 175 | 4.7 | Replication, recombination and repair |
| B | 2 | 0.1 | Chromatin structure and dynamics |
| D | 35 | 0.9 | Cell cycle control, cell division, chromosome partitioning |
| Y | 0 | 0.0 | Nuclear structure |
| V | 58 | 1.6 | Defense mechanisms |
| T | 190 | 5.1 | Signal transduction mechanisms |
| M | 156 | 4.2 | Cell wall/membrane biogenesis |
| N | 6 | 0.2 | Cell motility |
| Z | 0 | 0.0 | Cytoskeleton |
| W | 0 | 0.0 | Extracellular structures |
| U | 36 | 1.0 | Intracellular trafficking and secretion, and vesicular transport |
| O | 134 | 3.6 | Posttranslational modification, protein turnover, chaperones |
| C | 245 | 6.6 | Energy production and conversion |
| G | 259 | 7.0 | Carbohydrate transport and metabolism |
| E | 313 | 8.4 | Amino acid transport and metabolism |
| F | 91 | 2.4 | Nucleotide transport and metabolism |
| H | 194 | 5.2 | Coenzyme transport and metabolism |
| I | 179 | 4.8 | Lipid transport and metabolism |
| P | 176 | 4.7 | Inorganic ion transport and metabolism |

| | | | |
|---|-------|------|--|
| Q | 152 | 4.1 | Secondary metabolites biosynthesis, transport and catabolism |
| R | 478 | 12.8 | General function prediction only |
| S | 282 | 7.6 | Function unknown |
| - | 1,218 | 26.9 | Not in COGs |

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