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The Molecular Clockwork of the Fire Ant Solenopsis invicta

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Abstract

The circadian clock is a core molecular mechanism that allows organisms to anticipate daily environmental changes and adapt the timing of behaviors to optimize efficiency. In social insects, the ability to maintain the appropriate temporal order is thought to improve colony efficiency and fitness. We used the newly sequenced fire ant (Solenopsis invicta) genome to characterize the first ant circadian clock. Our results reveal that the fire ant clock is similar to the clock of the honeybee, a social insect with an independent evolutionary origin of sociality. Gene trees for the eight core clock genes, period, cycle, clock, cryptochrome-m, timeout, vrille, par domain protein 1 & clockwork orange, show ant species grouping closely with honeybees and Nasonia wasps as an outgroup to the social Hymenoptera. Expression patterns for these genes suggest that the ant clock functions similar to the honeybee clock, with period and cry-m mRNA levels increasing during the night and cycle and clockwork orange mRNAs cycling approximately anti-phase to period. Gene models for five of these genes also parallel honeybee models. In particular, the single ant cryptochrome is an ortholog of the mammalian-type (cry-m), rather than Drosophila-like protein (cry-d). Additionally, we find a conserved VPIFAL C-tail region in clockwork orange shared by insects but absent in vertebrates. Overall, our characterization of the ant clock demonstrates that two social insect lineages, ants and bees, share a similar, mammalian-like circadian clock. This study represents the first characterization of clock genes in an ant and is a key step towards understanding socially-regulated plasticity in circadian rhythms by facilitating comparative studies on the organization of circadian clockwork.


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Introduction

The circadian clock is a core molecular mechanism that allows organisms to anticipate daily environmental changes and adapt the timing of behaviors to maximize their efficiency. Although the components of the clock are largely conserved across a broad range of species, there is appreciable diversity in clock structure and function, particularly in insects [1–4]. The basic model of the molecular clock in Drosophila consists of positive and negative feedback loops involving a principle suite of canonical “clock genes” inside pacemaker cells [5]. The protein products of clock (Clk) and cycle (Cyc) genes interact and form a complex that binds to E-box elements in regulatory sequences of the period (Per) and timeless (Tim) gene promoter regions to activate transcription. Per and Tim mRNA accumulate in the cytoplasm during the night and the protein products enter the nucleus and bind to the CLK/CYC complex, inhibiting further transcription. On exposure to light, Drosophila-type cryptochrome (CRY-d) promotes rapid degradation of TIM that renders PER unstable. PER is eventually degraded, releasing the inhibition of transcription [6–9]. The activity of CRY-d allows the period and phase of the clock to adjust to changes in photoperiod [10]. Input pathways of the circadian clock respond to both environmental stimuli (including light and temperature) as well as social stimuli [8]. In fact, recent work has shown that the context of the social environment plays a major role in circadian rhythmicity in social insects [11–13]. Mapping the diversity in insect clock structure on an evolutionary backdrop of organisms that vary in key life history characteristics including social structure may reveal how evolution has shaped the various functions of the clock components [1,3,4,11,12,14].

In social insects, the ability to maintain the correct temporal order is not only important for individual success, but also plays a significant role in the success of the colony. Circadian timing is important for foraging activities, sun-compass navigation, timing of mating flights, and synchronization of individuals and the organization of colony tasks, such as nest maintenance [11,14,15]. Previous work has demonstrated that the circadian clock is associated with the division of labor in honeybees, bumble bees and ants, suggesting that the circadian clock is important for the social organization of insect societies [12,13–19]. The evolution of task-related plasticity in social insect colonies is thought to enhance task specialization and to improve colony efficiency; brood care
great ecological and economic importance [28,29]. Using the recent fire ant genome [30], we characterize eight putative principle clock genes, period (SiPer), cycle (SiCy), clock (SiClk), cryptochrome-m (SiCry-m), timeout (SiTim), vrille (SiVri), par domain protein 1 (SiPdp1) and the recently discovered clockwork orange gene (SiCwo) [31–33]. These genes were selected because they have well-documented functions in insect and/or mammalian clocks [5,6]. We use phylogenetic analyses to establish orthology/paralogy of the eight genes across insects and use qPCR analysis to determine how the clock mechanism is functioning at the molecular level. We develop gene models for five genes in order to determine the degree of conservation for domains present in the ant clock and shared with mammalian and Drosophila models. In addition, we describe a novel domain shared across insect orthologs of clockwork orange that is absent in vertebrates.

**Results**

Phylogenetic analyses of the principle clock genes show concordant patterns and confirm orthology. For each gene, orthologs from all ant species either form a monophyletic group or cluster in a polytomy with other Aculeata (bees, ants and wasps). In most analyses (with the exception of cycle), Nasumia, the non-social parasitic wasp, is the sister group to the Aculeata (Figure S1). On the tree for cryptochrome, the beekeepers (Bombus impatients) and honeybees (Apis mellifera) form a clade that is nested within the Formicidae (Figure 1). The Cyp orthologs found in the Hymenoptera clearly group with Cry2/CRY-m (mammalian-like Cyp) with the Drosophila-like Cyp1/Cry-d being only distantly related. The first phylogeny for clockwork orange in insects shows similar relationships as the other core clock genes and also shows the relationship between insect CWO and mammalian orthologs DEC1 and DEC2 (Figure 2).

The gene models for clock, cryptochrome, cycle and period for Solenopsis contain all of the conserved domains and binding regions found in insect species with high amino acid similarity to *Apis* in conserved regions (Figure S2). In the cryptochrome-m model, the fire ant ortholog, SiCry-m, clearly contains the NLS (nuclear localization signal) region found in mammalian-like cryptochromes that are absent in *Drosophila*-like cryptochromes (Figure 3). In addition, the amino acid sequence surrounding this region has low similarity to *Drosophila*-like cryptochromes relative to mammalian-like cryptochromes.

In the model for clockwork orange, the protein domains on CWO sequences that are shared between vertebrates and insects include bHLH, basic-helix-loop-helix, Hairy Orange and an NLS. Additional protein domains found on the vertebrate DE2C sequence including an Ala/Gly-rich domain and an HDAC interacting domain are not found on the insect orthologs. EST reads and directed PCR amplifications of the putative C-terminal region revealed stop codons in different positions, suggesting that siCWO may have several alternative splice variants. Our comparative analysis of the 3' end of the gene across insects revealed an additional conserved domain not yet described for this gene, called clockwork orange C-tail Domain, CWOCD (Figure 4). The domain contains a conserved VIPFALH C-tail region that is present in all the putative orthologous insect sequences that were analyzed in this study. The 57-62 amino acids in this domain are largely conserved among insects (e.g., ants and bees are similar at 52/58 sites in this region) and have little similarity to the Ala/Gly-rich domain in C-tail of vertebrate DE2C, the vertebrate ortholog of CWO [33,34]. Analysis of the CWOCD C-tail by Blastp algorithm (NCBI) showed that similar sequences are also
The expression patterns of the eight principle clock genes suggest that the circadian clock of *S. invicta* functions similar to the honey bee clock (Figures 5, 6; Table 1). *SiPer* and *SiCry-m* oscillate with a similar phase—mRNA levels increase in the evening and peak during the dark phase (R^2adj = 0.79, p = 0.003 and R^2adj = 0.49, p = 0.015; respectively). *SiCyc* and *SiCwo* oscillate anti-phase to *SiPer* (R^2adj = 0.54, p = 0.02 and R^2adj = 0.60, p = 0.012 respectively). Weak oscillations for *SiVri* are similar in phase to *SiCyc* and *SiCwo* (R^2adj = 0.63, p < 0.0001). *SiTim2* has significant, weak oscillations (R^2adj = 0.55, p = 0.019) but patterns are not consistent within individual colonies. *SiPdp1* and *SiClk* do not show significant, consistent oscillations across colonies (R^2adj = −0.2, p = 0.32 and R^2adj = 0.19, p = 0.01 respectively). There are no significant differences over time for the control gene, EF1α (ANOVA F = 1.40, p = 0.29).

**Discussion**

The Molecular Clockwork in the Ant is Similar to that in the Honey Bee

The molecular dissection of the fire ant circadian clock reveals that ants have a mammalian-like clock with high similarity to the
Figure 2. Parsimony tree for clockwork orange orthologs. Shown is a consensus tree with bootstrap values from 250 replicates. Insect CWO orthologs clearly separate from mammalian orthologs Dec1 & Dec2.
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Figure 3. Schematic models for CRY proteins from various animals. The protein models depicted are from the fire ant Solenopsis invicta (siCRY), the Western honey bee Apis mellifera (amCRY-m), the fruit fly Drosophila melanogaster (dmCRY), the Monarch butterfly Danaus plexippus (dpCRY1) the jewel wasp Nasonia vitripennis (nvCRY) and the domestic mouse Mus musculus (mmCRY1). Highlighted areas on the diagrams represent putative functional domains and motifs. The numbers below the domains indicate percents of identity/similarity to corresponding sequences on the protein of the fire ant. The numbers at the end of each diagram indicate the predicted protein size (number of amino acid residues). The protein domains on the CRY sequence are:

- **N**FAD binding. Proteins containing this domain are photolyases (DNA repair enzymes) or function as blue light photoreceptors (Pfam domain accession number: PF03441).
- **N**DNA photolyase. This domain is an evolutionary conserved protein domain from bacteria to mammals. It binds to UV-damaged DNA containing pyrimidine dimers and, upon absorbing a near-UV photon 300 to 500 nm, breaks the cyclobutane ring joining the two pyrimidines of the dimer (Pfam domain accession number: PF00875).
- **N**ICAT - Inhibition CLOCK-ARNTL Transcription. A domain required for the inhibition of CLOCK-ARNTL-mediated transcription (Swiss-Prot record of mmCRY1 accession number: P97784).
- **N**RD-2b – A domain defined by [58] based on studies with the clock proteins of the zebrafish. The domain is necessary for nuclear localization and the repression of CLOCK:BMAL-mediated transcription.
- **N**NLS - Nuclear localization signal in the RD-2b region, following [58].
- **N**EST - Expressed sequence tags.
doi:10.1371/journal.pone.0045715.g003
Figure 4. Schematic models for Clockwork Orange (CWO) proteins from various insects. The depicted models are for the fire ant Solenopsis invicta (siCWO), the honey bee Apis mellifera (amCWO), the fruit fly Drosophila melanogaster (dmCWO), Red Flour Beetle Tribolium castaneum (tcCWO). Also shown are related proteins from the house mouse Mus musculus (mmDEC2) and zebrafish Danio rerio (drDEC2). Highlighted
honeybee clock. Our study represents the most complete molecular characterization of a hymenopteran clock to date. Sequences of the eight principle gene clones are more closely related to the honeybee orthologs than to those of Nasonia and expression patterns of these genes suggest the molecular clockwork of ants utilizes similar mechanisms as the bee clock. In addition, the gene models from the fire ant show that all genes contain the necessary domains for the predicted function of the genes according to a mammalian-like clockwork and lack key components that characterize Drosophila-like clocks.

The fact that fire ant clock orthologs are more similar to honeybee clock orthologs than Nasonia in phylogenetic analyses is consistent with the monophyly of the Aculeata; i.e., the hypothesis that ants are more closely related to bees than to chalcidoid wasps [35]. Genome-wide BLASTp searches of fire ant proteins against protein databases indicate that 47% of Solenopsis invicta genes have the strongest similarity to apoid sequences and an additional 22% similar to Nasonia [30]. It is well documented that the bee clock is intricately connected to the social biology of this species [14,18,19,36,37]. Because ants and bees evolved sociality independently, it was not clear whether both clades evolved similar molecular mechanisms for regulating the circadian clock. Our results suggest that the clocks of ants and bees are regulated by the same mechanisms.

One diagnostic feature of the similarity in function of ant and bee clocks is found in the cryptochrome gene model. Cryptochromes belong to the photolyase gene family. Photolyses have a high affinity for complementary DNA strands and break certain types of pyrimidine dimers that arise when a pair of thymine or cytosine bases on the same strand of DNA become covalently linked. Proteins containing this domain also function as blue light photoreceptors that mediate blue light-induced gene expression and modulation of circadian rhythms. In Drosophila, the cryptochrome ortholog (Cry-d) functions as a photoreceptor in brain cells [1]. The light-dependent function of the gene requires a highly variable C-terminal domain that permits the interaction of the gene with TIM1 (timelike, a gene not found in the ant or bee genome) [38]. In mammalian-type cryptochromes (Cry-m), the C-terminal region is divergent from Cry-d orthologs. In contrast, Cry-m orthologs share three RD domains that are not found in Cry-d genes. These domains are responsible for nuclear localization and for the repression of CLK/BMAL transcription [2]. Our results show ant genomes encode the Cry-m-type cryptochrome with high sequence similarity and comparable expression profiles to the honeybee ortholog. Two lines of evidence suggest that the Cry gene is a functional component of the circadian mechanism in ants, like it is in bees and mammals. First, Cry mRNAs continue to oscillate in complete darkness [DD] in another ant species, P. occidentalis (unpublished data). Second, sequence similarity between ant and bee models of this gene is high [98%] which suggests that the function of this gene is conserved [1].

Another diagnostic feature is whether the CYC protein contains a transactivation domain. CYC (typically called BMAL1 in mammals) proteins are transcriptional factors with PAS-bHLH domains. In honeybees, amCYC is phylogenetically related to Drosophila CYC, but contains a highly conserved C-terminal transactivation domain that is found in mammalian BMAL proteins. In addition, honeybees lack the C-terminal region on amCLK that is responsible for transcriptional activity in dmCLK. Our results show that ant orthologs to CYC and CLK parallel the structural features of honeybee clocks. Thus, we would predict similarity in the temporal pattern of gene expression in ants and bees. In bees, brain transcript levels of amCYC oscillate nearly anti-phase to amPer while amCLK does not oscillate [2,27,39]. In ants, two out of three nests showed strong oscillations in sCYC that were anti-phase to ssiPer oscillations. However, we also found a weak, non-significant trend in ssiClk under LD conditions. More data on the expression of clock in ants under DD conditions is necessary to determine whether the expression of this gene is under circadian influence in ants.

Our data provide the first report of qPCR gene expression patterns for VrIlle and Pdp1, two conserved basic zipper transcription factors, in Hymenopterans. SiVrIlle shows a possible daily oscillation antiphase to SiPer1 oscillations. SiPdp1 does not appear to oscillate in the fire ant. The expression pattern of SiVrIlle is similar to that found for aphids [40] and is not consistent with that seen in Drosophila, where transcripts for the gene are controlled by CLK/CYC complex. A whole brain microarray analyses suggest that amVrIlle mRNA levels do not vary during the day in both nurse and forager honey bees sampled in DD, but this finding has not been yet validated with qPCR [27]. Additional studies are needed for determining if the pattern (and function) of VrIlle expression differ in bees and ants.

Overall, there is a potential difference in the expression of VrIlle but the remarkable similarity of ant and bee clocks supports the hypothesis that the Hymenoptera clock diverged from the basal insect clocks that contained both mammalian and Drosophila types of Cry and Tim [2]. Although the clocks of social hemimetabolous insects, i.e. termites, have not yet been studied in detail, the holometabolous social insects appear to utilize a molecular clockwork that generally functions similar to mammalian clocks and have lost the set of clock genes that were retained in Drosophila [2]. Our results will facilitate comparative sociogenomic analyses of circadian rhythms in the Aculeata. Understanding the similarities and differences in the regulation of the ant and bee clocks may give new insight into the role of circadian rhythms in regulating colony behavior and will help determine whether mechanisms of chronobiological plasticity are shared across social insects [11,14,17].

**A Novel Clockwork Orange Domain in Insects**

Recent studies indicate the *clockwork orange* is an integral part of the circadian clockwork in Drosophila [31–33]. *Cwo* encodes a transcriptional repressor that is thought to compete with the CLK/CYC complex to bind to the E-box proteins [31]. The CWO protein also regulates itself by forming its own negative transactivation domain (CWOCD - Clockwork orange C-tail domain). The CWOCD is found in the *tim* gene model. Cryptochromes (Cry-m) proteins are transcriptional factors with PAS-bHLH domains that characterizes Drosophila, such as the photolyase gene family.

**Figure 1: Molecular Clockwork of the Fire Ant**

Inset: A sequence alignment of a new conserved domain discovered on the CWO protein sequence that we termed ‘Clockwork Orange C-tail Domain’. The sequence alignment of a new conserved domain discovered on the CWO protein sequence that we termed ‘Clockwork Orange C-tail Domain’. The best alignment is shown, according to the default CLUSTALX convention. The areas on diagrams represent putative functional domains and motifs. For more details see legend to Fig. 3. Inset shows a CLUSTALW multiple sequence alignment of a new conserved domain discovered on the CWO protein sequence that we termed ‘Clockwork Orange C-tail Domain’ (CWOCD) the CLUSTALW alignment includes several additional CWO proteins from drosophilid and ant species (see Table S3). Asterisks in the bottom of alignment indicate amino acids conserved between insects and vertebrates. Alignments were generated with CLUSTALW and colored with JalView.
of circadian oscillations in other core clock genes. The mammalian ortholog to Cyo, Dec2 is involved in sleep length shifts [41]. As yet, we do not understand the role of CWO in hymenopteran insects.

To our knowledge, our results present the first gene-tree and model comparing *clockwork orange* across insects. Our analysis highlighted the presence of a novel domain in this gene that is present in insect CWO proteins but not the mammalian orthologs DEC1 and DEC2. The discovery of this conserved insect-specific domain in CWO contrasts with the overall similarity of social insect and mammalian orthologs of PER, CRY-m, CLK and CYC. This suggests that hymenopteran and *Drosophila* clocks may operate differently for some of the core feedback loops in the molecular clockwork but may share a mechanism for regulating the feedback loop of *clockwork orange*, the particular function of which is yet unknown for insects. Interestingly, the expression pattern of *SiCwo* in this study parallels patterns seen in the mouse, with high levels of *SiCwo* transcript during the day (peak at CT6) and lower levels during the night. This is similar to the oscillation seen in honey bees (peak at CT7; [27]) and in contrast to the pattern seen in *Drosophila* where *Cyo* transcripts peak later at ∼CT12 [31–33]. Thus, the structure of the *clockwork orange* gene in ants matches the structure found in insect Cyo genes and the expression pattern suggests a possible involvement in the positive loop of the clock.

*Clockwork orange* encodes a transcriptional repressor that inhibits CLK-mediated activation via interactions with PER [33]. In *Drosophila*, evidence suggests that CWO acts primarily in the late night to terminate CLK/CYC-mediated transcription of target genes. CWO creates its own negative feedback system, as it is one of the target genes regulated by the CLK/CYC complex through canonical E-box sequences [31]. The mammalian homologues (DEC1 and DEC2) appear to operate with a similar feedback mechanism. The feedback loop involving CWO is essential for the development of circadian rhythms in flies because CWO-deficient strains of flies show disruptions in oscillations of core clock genes and arrhythmic behavior [33]. In addition, the direct suppression of core clock genes through the CWO negative feedback loop helps generate and sustain high-amplitude oscillations [33].

The discovery that *clockwork orange* activity regulates the amplitude of the other core genes in the *Drosophila* clock underscores the complexity of the integrated positive and negative feedback loops that comprise the insect clock. Given the extensive studies of the E-box mediated negative feedback system [5], one of the key components of the circadian clock, the finding that the *clockwork orange* gene can regulate circadian expression via the E-box demonstrates that the molecular mechanism for circadian rhythms likely has redundancy among its components. The high conservation of the CWOC/D sequence in the C-tail of the insects’ CWO proteins suggest that this domain has a conserved but yet unknown function. The difference between the C-tail of insects and vertebrates provides yet another clue as to how evolution has shaped the diversity of circadian clocks and their regulation.

**Materials and Methods**

**Development of Gene Models and EST Analyses**

We developed gene models for five clock proteins in the fire ant *Solenopsis invicta*: Cry, Cyc, Per, CLK and Cwo. Selected genes contained domains known to differ across species and/or had adequate information known from multiple species. To determine gene models, we first ran TBLASTN using *Drosophila* Cry, Cyc, Per, CLK or Cwo proteins. Subsequently, ruby/and/or script [http://bioinformatics.oxfordjournals.org/content/26/20/2617.short http://www.biomedcentral.com/1471-2105/10/221/abstract] were used to extract relevant subsets of the fire ant genome. Automated gene models were generated using MAKER2 [http://www.biomedcentral.com/1471-2105/12/491] and subsequently manually refined using Apollo [http://genomeweb.com/2002/3/12/research/0082; http://genome.cshlp.org/content/18/1/188.full]. Libraries of orthologous sequences were created by searching protein databases with the Blastp algorithm [http://nar.oxfordjournals.org/content/36/suppl_2/W5.short] and using siCRY, siCyc, siPER or siCLK protein sequences as a query. From the Blastp results, putative orthologs of CRY, CYC, PER or CLK were selected from species that are relatively well characterized (e.g. *Drosophila melanogaster* or the mouse) or of special interest (e.g. *Nasonia vitripennis*).

Swiss-Prot records for the mouse clock protein orthologs that have good annotation (marked regions) of the major clock domains were used to identify the protein domains on the mice proteins. Selected genes contained domains known to differ across species and/or had adequate information from multiple species. To determine gene models, we first ran TBLASTN using *Drosophila* Cry, Cyc, Per, CLK or Cwo proteins. Subsequently, ruby/and/or script [http://bioinformatics.oxfordjournals.org/content/26/20/2617.short http://www.biomedcentral.com/1471-2105/10/221/abstract] were used to extract relevant subsets of the fire ant genome. Automated gene models were generated using MAKER2 [http://www.biomedcentral.com/1471-2105/12/491] and subsequently manually refined using Apollo [http://genomeweb.com/2002/3/12/research/0082; http://genome.cshlp.org/content/18/1/188.full]. Libraries of orthologous sequences were created by searching protein databases with the Blastp algorithm [http://nar.oxfordjournals.org/content/36/suppl_2/W5.short] and using siCRY, siCyc, siPER or siCLK protein sequences as a query. From the Blastp results, putative orthologs of CRY, CYC, PER or CLK were selected from species that are relatively well characterized (e.g. *Drosophila melanogaster* or the mouse) or of special interest (e.g. *Nasonia vitripennis*).

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protein domain on the various orthologs were confirmed with the NCBI [43], SMART [44,45], Pfam [46], ProSite [47] and InterPro [48] databases. Additional domains and motifs were delineated based on sequences reported in the literature, and for which the appropriate citation is provided. The EBI Global Alignment program [49] was used to determine the degree of amino acid residue identity/similarity between domains on the S. invicta protein models and corresponding amino acid sequences on orthologs from other animals. Domains were defined as conserved only if the amino acid sequence identity is ≥40% compared with the domain sequence on the mouse orthologs proteins [50].

Available EST sequences provided confirmation for most regions of the protein models. The “Translate tool” from the ExPASy proteomics server was used to predict the amino acid sequence encoded by each EST nucleotide sequence. Sequences that encode predicted polypeptides without stop codons in the middle were selected. The CLUSTALX/CLUSTALW algorithm was used to align the predicted EST amino acid sequences to the corresponding MAKER/Apollo protein model, and the protein models were corrected according to the amino acids predicted based on the EST sequences.

For CWO, a library of CWO ortholog sequences was compiled using the annotated CWOs found in [51]. The original library was selected using sequences >20% identity to the corresponding siCWO sequence. The protein domain sequences and conserved regions were identified as above. The Stockholm Bioinformatics Center’s NucPred [http://www.sbc.su/se/maccallr/nucpred/cgi-bin/single.cgi] was used to search for putative nuclear localization signals [NLS]. The NLS sequence was predicted in all CWO proteins present in the model. It is located inside bHLH domain with 100% identity in ortholog CWO sequences analyzed in this study. Additional domains and motifs were delineated based on relevant literature in which their biochemical function was defined [32,34,41].

Five EST sequences clustered together with the siCWO model. One of these clusters contained gaps inside the alignment caused by regions in an EST sequence that were not present in the Apollo model for siCWO. Translation of directed PCR in this region confirmed the Apollo model, suggesting that the EST with the extra regions in its sequence may represent an unprocessed mRNA of siCWO.

### Phylogenetic Analysis for the Clock Gene Proteins

Amino acid sequences from the open reading frames of the eight principle clock genes were aligned to orthologs found in Genbank and the ant genome database (now FOURMIDABLE [52] and references in [30,53–57] ) using CLUSTALW in MEGA 5.0 (Table S1). Sequences of genes with highly variable C-tail regions were trimmed. Parsimony trees were constructed from the alignments using TNT phylogenetic software after exporting the data from SequenceMatrix. All analyses used 100 random addition runs with bootstrap values based on 250 replicates. For comparison, phylogenies were also constructed using maximum likelihood methods based on the JTT matrix-based model in MEGA 5.0. The robustness of the unrooted tree was assessed using bootstraps (1000 replicates).

### Gene Expression Analyses

Three Solenopsis invicta colonies were sampled from laboratory colonies housed at the USDA-ARS Center for Medical, Agricultural, and Veterinary Entomology in Gainesville, FL. Colonies were allowed to acclimate for 2 days in LD conditions (12 hours L/12 hours D) and on the third day, 20 foragers were collected from each colony at 7 timepoints (every 4 hours). Individuals were placed on dry ice immediately and remained frozen at −70°C until extraction. On the day of collection, samples were shipped overnight on dry ice. Total RNA was extracted from whole heads and pooled across 12 individuals for each source colony (Qiagen RNAz Micro Kit). Because ants were sampled in LD conditions, it is not possible to distinguish whether changes in gene expression over the day are a result of endogenous circadian rhythms, are influenced by gene expression responses to exogenous light patterns, or both.

Fire ant-specific primers were designed from exon-coding regions to amplify 60–120 bp regions for qPCR analyses. cDNA was synthesized from extracted total RNA preps using ABI TaqMan Gold Reverse Transcriptase reagents and random hexamers. The 10 uL reactions included 1.0 uL of RNA with 1 X TaqMan RT Buffer, 5.5 mM 25 mM MgCl2, 500 uM of each of the deoxyNTPs, 2.5 uM of the Random Hexamer primers, 0.4 U/uL of RNase Inhibitor and 1.5 U/uL of Multi-Scribe Reverse Transcriptase. Reactions were performed in triplicate for each sample at each time point. All reactions were run at 25°C for 10 minutes, 48°C for 30 minutes, 95°C for 5 minutes, and then stored at −20°C until quantitative PCR. For each cDNA replicate, gene expression was assayed on an ABI
7900 HT instrument using ABI Taqman Gold reagents with gene specific primers (Table S2). The 25 µl qPCR reactions for each gene included 3.5 µl of template cDNA with 1 X TaqMan Buffer A, 5.5 mM 25 mM MgCl2, 200 µM of 10 mM deoxyATP, 200 mM of 10 mM deoxyCTP, 400 mM of 10 mM deoxyGTP, 100 mM of deoxyUTP, 200 mM of each primer, 0.01 U/µl of AmpErase UNG and 0.025 U/µl of AmpFlaq Gold DNA Polymerase. To standardize clock gene expression, EF1α was used as a control for each cDNA replicate. The 25 µl qPCR reactions for the control included 1.5 µl of template cDNA and the same reaction mixture described above. The following primers were used for the control gene: SiEF1α Forward: GGCTCTGAGGGAGGCTTT, SiEF1α Reverse: CCGAGATGTCTTCTACGTGAA, SiEF1α Probe: CTGCCGATAACGTGCG. Real-time PCR reactions for target genes and SiEF1α were performed under the following conditions: 2 min at 50°C for one cycle, 10 min at 95°C for one cycle, 15 sec at 95°C, 1 min at 60°C, for 45 cycles. Data were analyzed using SDS 2.1 software and quantification of relative mRNA levels and standard errors were calculated using the ΔΔCt method (ABI User Bulletin).

Gene expression patterns for each colony were analyzed separately. Significant differences in gene expression over time were tested using a two-way ANOVA [colony, timepoint] for each gene. Significant differences in gene expression over time were compared to a cosinor model to determine how closely the oscillations fit a generalized circadian model using MATLAB and the equation detailed in [12]. Ten million simulations were run starting with random seeds. The top 400 values that best fit the cosinor model were averaged to obtain the R² and amplitude values. Significance values for the fit to the cosinor model were calculated in MATLAB. R² adjusted was calculated from the estimates of R2 according to [12]. Oscillations in genes were considered significant if both ANOVA p-values and R² were ≥0.05 and R² values explained a large portion of the variance (R²adj≥0.5).

Supporting Information

Figure S1 Additional phylogenetic trees. (PPTX)

Figure S2 Additional gene models. (PPTX)

Table S1 Sequences used for phylogenetic alignments and gene models. (DOCX)

Table S2 Primers used in expression analyses. (DOCX)

Table S3 Photo credits for gene models. (DOCX)

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Author Contributions

Conceived and designed the experiments: KKI GB RM YW. Performed the experiments: KKI YW AK DS. Analyzed the data: KKI YW AK GB RM. Contributed reagents/materials/analysis tools: KKI DS YW AK RM. Wrote the paper: KKI AK GB.

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