Molecular Mechanisms Underlying the Arabidopsis Circadian Clock

Norihito Nakamichi¹,²,*

¹RIKEN Plant Science Center, Plant Productivity Systems Research Group, Tsurumi, Yokohama, 230-0045 Japan
²Present address: Institute for Advanced Research, and Graduate School of Bioagricultural Sciences, Nagoya University, Furocho, Chikusa, Nagoya, 464-8601 Japan
*Corresponding author: E-mail. nnakamichi@psc.riken.jp; Fax, +81-45-503-9609
(Received June 15, 2011; Accepted August 21, 2011)

A wide range of biological processes exhibit circadian rhythm, enabling plants to adapt to the environmental day–night cycle. This rhythm is generated by the so-called ‘circadian clock’. Although a number of genetic approaches have identified >25 clock-associated genes involved in the Arabidopsis clock mechanism, the molecular functions of a large part of these genes are not known. Recent comprehensive studies have revealed the molecular functions of several key clock-associated proteins. This process has provided mechanistic insights into how key clock-associated proteins are integrated, and may help in understanding the essence of the clock’s molecular mechanisms.

Keywords: Arabidopsis thaliana • Circadian clock • Genetic circuit • Protein function.

Abbreviations: bHLH, basic helix–loop–helix; CCA1, CIRCADIAN CLOCK-ASSOCIATED 1; CCT, CONSTANS, CONSTANS-LIKE1 and TOC1; CHE, CCA1 HIKING EXPEDITION; CK2, CASEIN KINASE 2; CKB, CASEIN KINASE β SUBUNIT; ELF3, EARLY FLOWERING 3; ELF4, EARLY FLOWERING 4; FIO1, FIONA1; FKF1, FLAVIN BINDING, KELCH REPEAT, F-BOX1; GI, GIANTANEA; JMJ, JUMONJI; LHY, LATE ELONGATED HYPOCOTYL; LKP2, LOV KELCH PROTEIN2; LOV, light, oxygen, voltage; LUX, LUXARRHYTHMO; LWD, LIGHT-REGULATED WD; PCL1, PHOTOCLOCK 1; PR, Pseudo-receiver; PRMT5, PROTEIN LUXARRHYTHMO; RVE, REVEILLE; TCP, TEOSINTE BRANCHED1, CYCLOIDEA and PCF; TIC, TIME FOR COFFEE; TOC1, TIMING OF CAB EXPRESSION 1; ZTL, ZEITLUPE.

Introduction

Circadian rhythm is the temporal oscillation of genetic, metabolic and physiological processes based on the 24 h cycle, allowing organisms to anticipate day–night changes in the environment (Bunning 1967, Pittendrigh 1993). A wide variety of organisms from cyanobacteria to mammals display circadian rhythms at the level of metabolism, physiology and behavior under conditions in which there are no external time cues, indicating that these rhythms are driven by an endogenous timekeeping mechanism, the so-called ‘circadian clock’.

The circadian clock in Arabidopsis plants regulates a number of biological processes, such as rhythmic leaf movement (Bunning 1967, Millar et al. 1995), petal opening (Bunning 1967), the elongation rate of stems, hypocotyls and roots (Lechaury 1985, Dowson-Day and Millar 1999, Nozue et al. 2007, Yazdanbakhsh et al. 2011), circumnutation of stems (Niinuma et al. 2005), central and secondary metabolite biosynthesis (Warren and Wilkins 1961, Kolosova et al. 2001, Blasing et al. 2005, Fukushima et al. 2009), hormone biosynthesis and responses (Thain et al. 2004, Covington and Harmer 2007, Covington et al. 2008, Michael et al. 2008, Mizuno and Yamashino 2008), water stress responses (Fowler et al. 2005, Bieniawska et al. 2008, Kidokoro et al. 2009, Legnaioli et al. 2009, Nakamichi et al. 2009), stomatal opening (Holmes 1986, Somers et al. 1998), Ca²⁺ concentrations in certain cellular compartments (Johnson et al. 1995, Xu et al. 2007), water uptake (Takase et al. 2011), seed dormancy (Penfield and Hall 2009) and defence against pathogens (W. Wang et al. 2011). In addition, the clock is used in some plants to measure the environmental photoperiod to induce inflorescence meristems (Bunning 1967), so that flowering occurs during the correct season (photoperiodic flowering) (Ganner and Allard 1920). These phenomena coordinateily contribute to fitness (or adaptive advantage) in 24 h day–night cycles (Green et al. 2002, Dodd et al. 2005, Yerushalmi et al. 2011).

Mutant screening and genetic mapping–cloning approaches have been taken in Arabidopsis in order to understand the molecular mechanisms of the plant clock (Millar et al. 1995). At least 25 genes associated with clock function have been identified by classical genetics strategies, as well as by reverse genetics (Fig. 1). A number of recent studies have revealed the molecular functions of clock-associated proteins, which have long been undetermined. These findings provide us for the first
time with enough information to understand how and when clock-associated proteins act in the circadian clock. It is now apparent that these genes interact to form a 'genetic circuit' which underlies the 24 h endogenous cycle. In this review, recent studies on the temporal and functional characterization of clock-associated proteins are summarized, followed by a discussion of how these proteins are integrated into the genetic circuit in the clock.

Clock-associated genes in Arabidopsis

Identification of clock genes began with traditional genetic approaches in the 1990s. Several key genes, including TIMING OF CAB EXPRESSION 1 (TOC1), ZEITLUPE (ZTL), TEJ, TIME FOR COFFEE (TIC), LUXARRHYTHMO [LUX or PHYTOCLOCK 1 (PCL1)], FIONA1 (FIO1) and PROTEIN ARGinine METHYl TRANSFERASE 5 (PRMT5), were isolated via large-scale screening experiments using gene promoters controlled under the circadian clock (e.g. chlorophyll a/b-binding protein, Cab) (Somers et al. 2000, Strayer et al. 2000, Panda et al. 2002, Hall et al. 2003, Hazen et al. 2005b, Onai and Ishiura 2005, Kim et al. 2008, Hong et al. 2010, Sanchez et al. 2010). Furthermore, the screening of mutants impaired in biological processes regulated by the circadian clock, such as photoperiodic flowering and hypocotyl elongation, led to the isolation of EARLY FLOWERING 3 (ELF3), ELF4, GIANTANEA (GI) and LATE ELONGATED HYPOCOTYL (LHY) (Schaffer et al. 1998, Fowler et al. 1999, Park et al. 1999, Hsu et al. 2011).
Several approaches have been used to identify other key clock-associated genes. CIRCADIAN CLOCK ASSOCIATED 1 (CCA1) and CCA1 HIKING EXPEDITION (CHE) were identified by isolating proteins that bind to rhythmic gene promoters (Wang et al. 1997, Wang and Tobin 1998, Pruneda-Paz et al. 2009). Reverse genetics approaches have identified four TOC1 homologs, PSEUDO-RESPONSE REGULATOR 9 (PRR9), PRR7, PRR5 and PRR3, as components of the clock (Matsushika et al. 2000, Eriksson et al. 2003, Michael et al. 2003, Yamamoto et al. 2003, Para et al. 2007). Functional redundancies among genes showing high sequence similarities are often observed in Arabidopsis, which may make further discovery of novel clock-associated genes by a classical genetic approach technically challenging. For example, independent large-scale mutagenesis screenings identified allelic mutants, suggesting that these screenings were saturated (Onai et al. 2004, Hazen et al. 2005a). Biochemical and reverse genetic approaches, however, have identified new genes. Chemical genetics is emerging as a method which can also transcend the problem of functional redundancy by targeting specific receptor–ligand or other small molecule interactions.

MYB transcription factors take the ‘early shift’

CCA1 and LHY (CCA1/LHY) are the closest paralogs of a single MYB transcription factor expressed with a morning acrophase, indicating that these genes take the ‘early shift’ in clock regulation, corresponding to early morning duty in a shift-work labor system (Fig. 2A) (Wang et al. 1997, Schaffer et al. 1998, Wang and Tobin 1998, Perales and Mas 2007). Overexpression of CCA1 or LHY abolishes the rhythms of clock output genes under constant light conditions (Schaffer et al. 1998, Wang and Tobin 1998). Single mutations in the cca1 or lhy loci have a short period phenotype, and cca1 lhy double mutants have a shorter period than either single mutation alone, indicating that CCA1/LHY are redundant but that both are required for proper clock function (Green and Tobin 1999, Alabadi et al. 2002, Mizoguchi et al. 2002). CCA1/LHY bind to a CCA1-binding site (AAACAATCT or AAAAATCT) and to an evening element (AAAAATATCT) (Wang et al. 1997, Alabadi et al. 2001). They repress the transcription of TOC1, ELF4 and LUX (Alabadi et al. 2001, Hazen et al. 2005b, Perales and Mas 2007, Li et al. 2011), but activate the transcription of PRR9 and PRR7 through these binding sites (Farre et al. 2005) (Fig. 2A).

CCA1 function is subject to post-translational modification. CCA1 is phosphorylated by the protein kinase CASEIN KINASE 2 (CK2), which is required for the formation of a DNA–protein complex containing CCA1 (Sugano et al. 1998, Sugano et al. 1999). Overexpressors of the CKB3 regulatory subunit of CK2 (Sugano et al. 1998), or CKB4 (Perales et al. 2006), which exhibits higher CK2 activity, display a short-period phenotype. On the other hand, overexpression of a mutant CCA1 which cannot be phosphorylated by CK2 does not result in a hypermorphic phenotype (Daniel et al. 2004), suggesting that CCA1 phosphorylation by CK2 is necessary for its function in the Arabidopsis clock. However, in rice it is unlikely that CK2 is involved in the clock mechanism. This difference was partly attributed to the lack of a serine residue, which is a CK2 target site, in OsLHY (a CCA1 ortholog), implying the divergence of post-translational regulation of CCA1 and LHY in higher plants during evolution (Ogiso et al. 2010).

Among the seven close homologs of CCA1/LHY in Arabidopsis, EARLY-PHYTOCHROME-RESPONSIVE 1 or REVEILLE 7 (RVE7) (Kuno et al. 2003), CIRCADIAN 1 or RVE2 (Zhang et al. 2007), and RVE1 (Rawat et al. 2009) have been implicated in the output function of the clock. Recently, however, it was shown that one member of the homolog set, RVE8 or LHY-CCA1-LIKE 5, is involved in the clock by directly activating the expression of both TOC1 and PRR5 (Farinas and Mas 2011, Rawat et al. 2011).

PRR9, PRR7 and PRR5 take the ‘day and swing shifts’

PRR9, PRR7 and PRR5 (PRRs) are sequentially expressed from early daytime until around midnight, corresponding to the ‘day shift’ and ‘swing shift’ in this metaphorical shift-work system (Farre and Kay 2007, Ito et al. 2007b, Kiba et al. 2007, Fujiwara et al. 2008, Nakamichi et al. 2010) (Fig. 2B). They possess a pseudo-receiver (PR) domain at their N-termini, and a CONSTANS, CONSTANS-LIKE1 and TOC1 (CCT) motif at their C-termini (Makino et al. 2000, Matsushika et al. 2000, Strayer et al. 2000).

Genetic studies have shown that PRR9, PRR7 and PRR5 function redundantly and/or synergistically within the clock mechanism (Farre et al. 2005, Nakamichi et al. 2005, Salome and McClung 2005). Given that expression of CCA1 and LHY is decreased in PRR7 or PRR5 overexpression lines (Sato et al. 2002, Farre and Kay 2007), and increased in prr9 prr7 prr5 and prr9 prr7 prr5 mutants (Farre et al. 2005, Nakamichi et al. 2005, Salome et al. 2010), these PRR genes are likely to be negative regulators of CCA1 and LHY. A recent study demonstrated that these PRR proteins associate with CCA1 and LHY promoters in vivo, and repress these genes from early daytime until midnight (Nakamichi et al. 2010) (Fig. 2B). Each PRR protein works at a specific time; PRR9 functions during early daytime, PRR7 is active from early daytime until midnight, and PRR5 works from noon until midnight. PRRs seem to act as active transcriptional repressors, because the repression motif, which confers transcriptional repressor activity on the yeast GAL4 DNA-binding domain, is present in the PRRs (Nakamichi et al. 2010). However, it is not yet known how the PRRs are recruited to the CCA1 and LHY promoter regions. Given that the CCT motif of CONSTANS is involved in interactions with the target DNA (Wenkel et al. 2006, Tiwari et al. 2010), it is possible that the CCT motif of PRRs is also involved.
in interactions with target DNA regions. In addition, PRR proteins participate in post-translational regulation. PRR5 interacts with TOC1 through its PR domains, and enhances phosphorylation and nuclear localization of TOC1 (Wang et al. 2010) (Fig. 2C).

‘The graveyard shift’: TOC1, ELF3, ELF4 and LUX

The toc1-1 mutant was the very first Arabidopsis clock mutant found, identified because of its short-period phenotype.
Molecular mechanism of the circadian clock

TOC1 proteins are expressed during the night, the time of the ‘graveyard shift’ (Makino et al. 2000, Matsushika et al. 2000, Strayer et al. 2000). Reduction of TOC1 expression by RNA interference (RNAi) shortens the period length, whereas increased TOC1 expression under the control of its own promoter results in a lengthened period (Mas et al. 2003a), suggesting that both the timing and level of TOC1 expression are crucial for maintaining a proper period length. TOC1 is thus subjected to multiple layers of regulation. In addition to the transcriptional and post-transcriptional regulation of TOC1 described in earlier sections (Fig. 2A, C), TOC1 is targeted for degradation by ZTL family proteins (Fig. 2C) (Mas et al. 2003b, Kim et al. 2007, Baudry et al. 2010). On the other hand, TOC1 is stabilized by PRR3 via protein–protein interactions (Fig. 2C) (Para et al. 2007).

The exact molecular function of TOC1 within the circadian clock remained elusive for a long time, but recent studies indicate that TOC1 is a transcriptional regulator. TOC1 activates CCA1 expression by antagonizing the action of CHE, a repressor of CCA1 (Pruneda-Paz et al. 2009) (Fig. 2C). CHE is a TCP (for TEOSINTE BRANCHED1, CYCLOIDEA and PCF) transcription factor. Other TCPs also have the ability to bind to TOC1 (Giraud et al. 2010), implying that TOC1 activates CCA1 expression through its binding to TCPS.

ELF3, ELF4 and LUX are essential for sustaining the circadian rhythm under constant light conditions, since mutations in each gene result in arrhythmia (Hicks et al. 1996, Doyle et al. 2002, Hazen et al. 2005b, Onai and Ishiura 2005). ELF3, ELF4 and LUX are expressed from evening until midnight. All three genes are required for full CCA1 and LHY expression, as evidenced by decreased expression of CCA1 and LHY in elf3, elf4 and lux mutants (Doyle et al. 2002, Hazen et al. 2005b, Kakiz et al. 2005, Onai and Ishiura 2005). ELF3, ELF4 and LUX encode structurally distinct proteins: ELF3 encodes a putative transcriptional regulator, ELF4 encodes a protein with unknown function, and LUX encodes a GARP-type MYB transcription factor. Recent studies indicate that ELF3 and ELF4 are transcriptional repressors of PRR9 and PRR7, and that LUX is a night-time repressor of PRR9 (Dixon et al. 2011, Helfer et al. 2011) (Fig. 2C). LUX also directly represses its own expression by binding to the LUX promoter, forming a negative feedback loop (Helfer et al. 2011).

The ZTL–GI complex as a light sensor

ZTL is the best characterized factor involved in post-translational regulation of clock-associated proteins. ZTL protein contains an F-box domain, which is a component of the Skp/Cullin/F-box E3 ubiquitin ligases acting in the proteosome-dependent protein degradation pathway. In addition, this protein possesses an N-terminal LOV (light, oxygen, voltage-dependent) domain that perceives blue light, suggesting that ZTL functions as a blue light-regulated F-box protein. Indeed, ZTL targets TOC1 and PRR5 for degradation in the absence of blue light (Mas et al. 2003b, Kiba et al. 2007). There are two ZTL homologs in Arabidopsis: FLAVIN BINDING, KELCH REPEAT, F-BOX1 (FKF1) (Nelson et al. 2000, Imaizumi et al. 2003, Sawa et al. 2007) and LOV KELCH PROTEIN2 (LKP2) (Schultz et al. 2001). A recent study indicated that all members of the ZTL protein family are engaged in PRR5 and TOC1 degradation (Baudry et al. 2010).

Recently, Kim et al. (2007) demonstrated that ZTL oscillation (low in the morning; high in the evening) is established and sustained by blue light-enhanced interaction with GI, which is a factor responsible for the robustness of the rhythm, but with no known functional domain (Kim et al. 2007). The blue light-activated ZTL forms a complex with GI, resulting in stabilization of ZTL. In darkness, the complex is attenuated, thereby destabilizing ZTL. Because the timing of GI expression is determined by the clock, complex formation is also under clock control (David et al. 2006). The external light conditions and internal circadian clock together confer fine-tuned rhythms to ZTL, leading to robust TOC1 and PRR5 oscillations (Kim et al. 2007) (Fig. 2B, C).

Other, but indispensable, factors

There are some clock-associated proteins which are known to be involved in rhythmic control, but whose specific molecular function remains unknown. For example, TEJ (TEJ means ’bright’ in Sanskrit) encodes a poly(ADP-ribose) glycohydrolase, which is involved in poly(ADP-ribosylation) of proteins (Panda et al. 2002). A tej mutation lengthens the circadian period. TEJ targets have not been identified.

TIC was named for the evidence that the gene is required for maintaining metabolic rhythm from mid- to late night when human activity often gets a boost from caffeine coffee (Hall et al. 2003). TIC encodes a nuclear-localized protein with probable ATP/GTP-binding site A motifs (P-loop) (Ding et al. 2007). Interestingly, the abundance and cellular localization of TIC are not under clock control, implying that some unknown factor or factors restricts the activity of TIC during the night (Ding et al. 2007).

A mutation in FIO1 (fiona means ‘flowering’ in Korean) results in longer circadian periods (Kim et al. 2008). FIO1 encodes a nuclear-localized protein with a DUF890 domain, which is found in the methyltransferase superfamily, though the precise function of FIO1 remains to be elucidated.

LIGHT-REGULATED WD1 (LWD1) and its closest homolog, LWD2, encode WD repeat-containing proteins (Wu et al. 2008). The lwd1 lwd2 double mutant has a short-period phenotype. Recently, it was shown that LWD1 associates with the promoter region of PRR9 to activate PRR9 expression (Y. Wang et al. 2011).

Two transcription factors, MYB3R2 and BHLH69A, were identified through systematic screening in which transcription factors were tested for their potential to alter circadian rhythms.
(Hanano et al. 2008). Although circadian periods were lengthened both in MYB3R2 and bHLH69A overexpression lines, the direct target of MYB3R2 and bHLH69 has not been identified.

A junomycin-C (JmC) domain-containing protein (JMD5 = JM30) gene, encoding a possible histone demethylase, was identified as a clock component (Jones et al. 2010, Lu et al. 2011). Mutations in JMD5 result in shortened circadian periods, and the mutation enhances the effect of a toc1 mutation, suggesting that JMD5 interacts synergistically with TOC1 (Jones et al. 2010).

Recently, PRMT5, which is involved in site-specific alternative splicing, was implicated in the clock mechanism (Hong et al. 2010, Sanchez et al. 2010). PRMT5 acts by dimethylating Sm proteins which participate in pre-mRNA splicing. The loss-of-function prmt5 mutation results in a long-period phenotype. Splicing of the third intron of PRR9 is impaired in prmt5, and the prr9 prr7 double mutation is epistatic to prmt5, suggesting that PRMT5 controls the period length in part by regulating PRR9 splicing.

**Genetic circuit in the clock**

Based on our current knowledge of the regulation and molecular functions of clock-associated genes, a ‘genetic circuit’ model has been proposed (Helfer et al. 2011). Three classes of repressors constitute the genetic circuit: (i) morning-phase proteins CCA1 and LHY repress ELF4 and LUX; (ii) evening-phase proteins ELF4 and LUX repress PRR9 and PRR7; and (iii) mid-day-phase proteins PRR9 and PRR7 repress CCA1 and LHY. Although there is no experimental evidence to show that the dynamics of the proposed circuit is responsible for clock function, a synthetic genetic circuit, known as ‘the repressilator’, which is a cyclic negative feedback loop composed of three transcriptional repressor genes, can produce an oscillating pattern (Elowitz and Leibler 2000). The sustainable oscillation in ‘the repressilator’ is dependent on similar decay rates of protein and mRNA, and large amounts of protein at its peak level. Oscillation patterns can also be generated in networks containing an activator and a repressor, or an odd number of repressors over three, if stochastic characters are negligible in the networks. Such theoretical approaches help to understand the molecular basis and dynamics of the clock.

**Perspectives**

Recent progress in genome research indicates that clock-associated genes identified in Arabidopsis are mostly conserved among angiosperms (Song et al. 2010). Furthermore, evidence is accumulating that these genes are orthologs of corresponding genes in Arabidopsis, suggesting that the proposed molecular clock mechanism is conserved among angiosperms (ELF3, GI and LHY in duckweed (Miwa et al. 2006, Serikawa et al. 2008), LHY and TOC1 in poplar (Ibanez et al. 2010)), including agriculturally important plants [ELF4 and GI in pea (Hecht et al. 2007, Liew et al. 2009), and GI and LHY in rice (Ogiso et al. 2010, Izawa et al. 2011)]. A key trait in crops under clock control is photoperiodic flowering, a critical aspect of crop production that has been selected during domestication. For example, photoperiod-insensitive wheat varieties predominate in relatively warm regions where wheat needs to flower and mature before the onset of high summer temperatures. A genetic locus responsible for advancing the heading date of such varieties is present at the upstream region of the PRR7 homolog (Ppd-D1a), which causes misexpression of this gene (Beales et al. 2007). On the other hand, mutations in a PRR7 homolog (Ppd-H1) were found as the genetic loci which delay the heading date of spring-sown barley (Turner et al. 2005). The Ppd-H1 varieties have an extended vegetative growth phase and ultimately higher yields in Western Europe and North America. Quantitative trait loci for flowering time overlap with PRR7 homologs in rice and *Brassica* *rapa* (Murakami et al. 2005, Lou et al. 2011). Furthermore, GI and ELF4 orthologs were identified as the genetic loci that alter photoperiodic flowering in pea (Hecht et al. 2007, Liew et al. 2009). Therefore, studies of the Arabidopsis circadian clock should enable us to understand how plants generate responses to photoperiod, and thus to induce flowering, which will ultimately be a significant boon for agriculture.

Thanks to recent studies, the molecular functions and functional timing (duration) of many Arabidopsis clock-associated proteins have been determined, which has enabled us to propose a ‘genetic circuit’ model. Although it is widely accepted that the genetic circuit plays an important role in the clock system, whether or not the genetic circuit alone drives these rhythms is an open question. Since the transcriptional process is generally stochastic and depends on temperature and metabolic conditions (Raser and O'Shea 2005), and the circadian period is constant over a wide temperature range (known as temperature compensation), a genetic circuit alone does not meet the theoretical requirements for clock function. Recently, a post-translational (or non-transcriptional) oscillation was detected in cyanobacteria and the unicellular green alga *Ostreococcus* *tauri* (Nakajima et al. 2005, Tomita et al. 2005, O’Neill et al. 2011), which also possess transcription-based feedback loops (Kitayama et al. 2008, Corellou et al. 2009). The post-translational oscillators are coupled with transcription-based feedback loops in cyanobacteria and the green algae under physiological conditions (Kitayama et al. 2008, O’Neill et al. 2011). Interestingly, the cyanobacterial post-translational oscillator is sufficient to drive circadian rhythm by itself under extremely poor metabolic conditions and throughout a wide temperature range, illustrating the resilient nature of circadian periodicity. Compensations in period length for temperature fluctuations and metabolic changes are embedded in the post-translational oscillator (Nakajima et al. 2005, Tomita et al. 2005, Ito et al. 2007a). Whether the post-translational oscillator functions in higher plants is an open and interesting question that needs to be addressed before we can understand how the circadian clock evolved, and exactly how it functions in...
controlling the plant circadian clock. It is likely that answers to these questions will provide insights into many of the critical features of plant behavior.

**Funding**

Preparation of this review was supported by the Special Postdoctoral Researcher’s Program; Yokohama Institute Director’s Discretionary Fund; Technology Transfer Office Fund, from RIKEN.

**Acknowledgments**

Special thanks go to Drs. Takatoshi Kiba (RIKEN Plant Science Center) and Hiroshi Ito (Ochanomizu University) for critical reading of the manuscript.

**References**

Alabadi, D., Oyama, T., Yanovsky, M.J., Harmon, F.G., Mas, P. and Kay, S.A. (2001) Reciprocal regulation between TOC1 and LHY/CCA1 within the Arabidopsis circadian clock. *Science* 293: 880–883.

Alabadi, D., Yanovsky, M.J., Mas, P., Harmer, S.L. and Kay, S.A. (2002) Critical role for CCA1 and LHY in maintaining circadian rhythmicity in Arabidopsis. *Curr. Biol.* 12: 757–761.

Baudry, A., Ito, S., Song, Y.H., Strait, A.A., Kiba, T., Lu, S. et al. (2010) F-box proteins FK/F1 and LKP2 act in concert with ZEITLUPE to control Arabidopsis clock progression. *Plant Cell* 22: 606–622.

Beales, J., Turner, A., Griffiths, S., Snape, J.W. and Laurie, D.A. (2007) A pseudo-response regulator is misexpressed in the photoperiod insensitive Ppd-D1a mutant of wheat (Triticum aestivum L.). *Theor. Appl. Genet.* 115: 721–733.

Bieniawska, Z., Espinoza, C., Schlereth, A., Sulpic, R., Hincha, D.K. and Hannah, M.A. (2008) Disruption of the Arabidopsis circadian clock is responsible for extensive variation in the cold-responsive transcriptome. *Plant Physiol.* 147: 263–279.

Blasing, O.E., Gibon, Y., Gunther, M., Hohne, M., Morcuende, R., Osuna, D. et al. (2005) Sugars and circadian regulation make major contributions to the global regulation of diurnal gene expression in Arabidopsis. *Plant Cell* 17: 3257–3281.

Bunning, E. (1967) The Physiological Clock. The Heidelberg Science Library, Springer-Verlag, New York.

Corellou, F., Schwartz, C., Motta, J.P., Djouani-Tahri el, B., Sanchez, F. and Bouget, F.Y. (2009) Clocks in the green lineage: comparative functional analysis of the circadian architecture of the picoeukaryote ostreococcus. *Plant Cell* 21: 3436–3449.

Covington, M.F. and Harmer, S.L. (2007) The circadian clock regulates auxin signaling and responses in Arabidopsis. *PLoS Biol.* 5: e222.

Covington, M.F., Maloof, J.N., Straume, M., Kay, S.A. and Harmer, S.L. (2008) Global transcriptome analysis reveals circadian regulation of key pathways in plant growth and development. *Genome Biol.* 9: R130.

Daniel, X., Sugano, S. and Tobin, E.M. (2004) CK2 phosphorylation of CCA1 is necessary for its circadian oscillator function in Arabidopsis. *Proc. Natl Acad. Sci. USA* 101: 3292–3297.

Davies, K.M., Armbruster, U., Tama, N. and Putterill, J. (2006) Arabidopsis GIGANTEA protein is post-transcriptionally regulated by light and dark. *FEBS Lett.* 580: 1193–1197.

Ding, Z., Millar, A.J., Davis, A.M. and Davis, S.J. (2007) TIME FOR COFFEE encodes a nuclear regulator in the Arabidopsis thaliana circadian clock. *Plant Cell* 19: 1522–1536.

Dixon, L.E., Knox, K., Kozma-Bognar, L., Southern, M.M., Pokhilko, A. and Millar, A.J. (2011) Temporal repression of core circadian genes is mediated through EARLY FLOWERING 3 in Arabidopsis. *Curr. Biol.* 21: 120–125.

Dodd, A.N., Salathia, N., Hall, A., Kevei, E., Toth, R., Nagy, F. et al. (2005) Plant circadian clocks increase photosynthesis, growth, survival, and competitive advantage. *Science* 309: 630–633.

Dowson-Day, M.J. and Millar, A.J. (1999) Circadian dysfunction causes aberrant hypocotyl elongation patterns in Arabidopsis. *Plant J.* 17: 63–71.

Doyle, M.R., Davis, S.J., Bastow, R.M., McWatters, H.G., Kozma-Bognar, L., Nagy, F. et al. (2002) The ELF4 gene controls circadian rhythms and flowering time in Arabidopsis thaliana. *Nature* 419: 74–77.

Elowitz, M.B. and Leibler, S. (2000) A synthetic oscillatory network of transcriptional regulators. *Nature* 403: 335–338.

Eriksson, M.E., Hanano, S., Southern, M.M., Hall, A. and Millar, A.J. (2003) Response regulator homologues have complementary, light-dependent functions in the Arabidopsis circadian clock. *Planta* 218: 159–162.

Farinas, B. and Mas, P. (2011) Functional implication of the MYB transcription factor RVE8/LCL1 in the circadian control of histone acetylation. *Plant J.* 66: 318–329.

Farre, E.M., Harmer, S.L., Harmon, F.G., Yanovsky, M.J. and Kay, S.A. (2005) Overlapping and distinct roles of PRR7 and PRR9 in the Arabidopsis circadian clock. *Curr. Biol.* 15: 47–54.

Farre, E.M. and Kay, S.A. (2007) PRR7 protein levels are regulated by light and the circadian clock in Arabidopsis. *Plant J.* 52: 548–560.

Fowler, S.G., Cook, D. and Thomashow, M.F. (2005) Low temperature induction of Arabidopsis CBF1, 2, and 3 is gated by the circadian clock. *Plant Physiol.* 137: 961–968.

Fowler, S., Lee, K., Onouchi, H., Samach, A., Richardson, K., Morris, B. et al. (1999) GIGANTEA: a circadian clock-controlled gene that regulates photoperiodic flowering in Arabidopsis and encodes a protein with several possible membrane-spanning domains. *EMBO J.* 18: 4679–4688.

Fujisawa, S., Wang, L., Han, L., Suh, S.S., Salome, P.A., McClung, C.R. et al. (2008) Post-translational regulation of the Arabidopsis circadian clock through selective proteolysis and phosphorylation of pseudo-response regulator proteins. *J. Biol. Chem.* 283: 23073–23083.

Fukushima, A., Kusano, M., Nakamichi, N., Kobayashi, M., Hayashi, N., Sakakibara, H. et al. (2009) Impact of clock-associated Arabidopsis pseudo-response regulators in metabolic coordination. *Proc. Natl Acad. Sci. USA* 106: 7251–7256.

Garner, W.W. and Allard, H.A. (1920) Effect of the relative length of day and night and other factors of the environment on growth and reproduction in plants. *J. Agr. Res.* 18: 553–606.

Giraud, E., Ng, S., Carrie, C., Duncan, O., Low, J., Lee, C.P. et al. (2010) TCP transcription factors link the regulation of genes encoding mitochondrial proteins with the circadian clock in Arabidopsis thaliana. *Plant Cell* 22: 3921–3934.

Green, R.M., Tingay, S., Wang, Z.Y. and Tobin, E.M. (2002) Circadian rhythms confer a higher level of fitness to Arabidopsis plants. *Plant Physiol.* 129: 576–584.
Izawa, T., Mihara, M., Suzuki, Y., Gupta, M., Itoh, H., Nagasno, A.J. et al. (2011) Os-GIGANTEA confers robust diurnal rhythms on the global transcriptome of rice in the field. Plant Cell 23: 1741–1755.

Johnston, C.H., Knight, M.R., Kondo, T., Masson, P., Sedbrook, J., Haley, A. et al. (1995) Circadian oscillations of cytosolic and chloroplastic free calcium in plants. Science 269: 1863–1865.

Jones, M.A., Covington, M.F., Ditacchio, L., Vollmers, C., Panda, S. and Harmer, S.L. (2010) Lunromi domain protein MJMDs functions in both seedling and flowering time in Arabidopsis. Proc. Natl Acad. Sci. USA 107: 21623–21628.

Kiba, T., Henriques, R., Sakakibara, H. and Chua, N.H. (2007) Targeted degradation of PSEUDO-RESPONSE REGULATORS by an SCFTIR complex regulates clock function and photomorphogenesis in Arabidopsis thaliana. Plant Cell 19: 2516–2530.

Kidokoro, S., Maruyama, N., Nakashima, K., Imura, Y., Narusaka, Y., Shinwari, Z.K. et al. (2009) The phytomorph-interacting factor PIF7 negatively regulates DREB1 expression under circadian control in Arabidopsis. Plant Physiol. 151: 2046–2057.

Kikis, E.A., Khanna, R. and Quail, P.H. (2005) ELF4 is a phytochrome-regulated component of a negative-feedback loop involving the central oscillator components CCA1 and LHY. Plant J. 44: 300–313.

Kim, J., Kim, Y., Yeom, M., Kim, J.H. and Nam, H.G. (2008) FIONA1 is essential for regulating period length in the Arabidopsis circadian clock. Plant Cell 20: 307–319.

Kim, W.Y., Fujiwara, S., Suh, S.S., Kim, J., Kim, Y., Han, L. et al. (2007) ZEITLUPE is a circadian photoreceptor stabilized by GIGANTEA in blue light. Nature 449: 356–360.

Kitayama, Y., Nishiwaki, T., Terauchi, K. and Kondo, T. (2008) Dual KacB-based oscillations constitute the circadian system of cyanobacteria. Genes Dev. 22: 1513–1521.

Kolasova, N., Gorenstein, N., Kish, C.M. and Dudareva, N. (2001) Regulation of circadian methyl benzoate emission in diurnally and nocturnally emitting plants. Plant Cell 13: 2333–2347.

Kuno, N., Moller, S.G., Shinomura, T., Xu, X., Chua, N.H. and Furuya, M. (2003) The novel MYB protein EARLY-PHYTOCHROME-RESPONSIVE1 is a component of a slave circadian oscillator in Arabidopsis. Plant Cell 15: 2476–2488.

Lecharny, A., Schwall, M. and Wagner, E. (1985) Stem extension rate in light-grown plants. Plant Physiol. 79: 625–629.

Legnaioli, T., Cuevas, J. and Mas, P. (2009) TOC1 functions as a molecular switch connecting the circadian clock with plant responses to drought. EMBO J. 28: 3745–3757.

Li, G., Siddiqui, H., Teng, Y., Lin, R., Wan, X.Y., Li, J. et al. (2011) Coordinated transcriptional regulation underlying the circadian clock in Arabidopsis. Nat. Cell Biol. 13: 616–622.

Liew, L.C., Hecht, V., Laurie, R.E., Knowles, C.L., Vander Schoor, J.K., Macknight, R.C. et al. (2009) DIE NEUTRALIS and LATE BLOOMER 1 contribute to regulation of the pea circadian clock. Plant Cell 21: 3198–3211.

Lou, P., Xie, Q., Xu, X., Edwards, C.E., Brock, M.T., Weinig, C. et al. (2011) Genetic architecture of the circadian clock and flowering time in Brassica rapa. Theor. Appl. Genet. 123: 397–409.

Lu, S.X., Knowles, S.M., Webb, C.J., Celaya, R.B., Cha, C., Sui, J.P. et al. (2011) The JmjC domain-containing protein MJM30 regulates period length in the Arabidopsis circadian clock. Plant Physiol. 115: 906–915.

Makino, S., Kiba, T., Imamura, A., Hanaki, N., Nakamura, A., Suzuki, T. et al. (2000) Genes encoding pseudo-response regulators: insights into His-to-Asp phosphorelay and circadian rhythm in Arabidopsis thaliana. Plant Cell Physiol. 41: 791–803.
Molecular mechanism of the circadian clock

Nozue, K., Covington, M.F., Duek, P.D., Lorrain, S., Fankhauser, C., Harmer, S.L. et al. (2007) Rhythmic growth explained by coincidence between internal and external cues. Nature 448: 358–361.

O'Neill, J.S., van Ooijen, G., Dixon, L.E., Troein, C., Corellou, F., Bouget, F.Y. et al. (2011) Circadian rhythms persist without transcription in a eukaryote. Nature 469: 554–558.

Ogiso, E., Takahashi, Y., Sasaki, T., Yano, M. and Izawa, T. (2010) The role of casein kinase II in flowering time regulation has diversified during evolution. Plant Physiol. 152: 808–820.

Onai, K. and Ishiura, M. (2005) PHYTOCLOCK 1 encoding a novel GARP protein essential for the Arabidopsis circadian clock. Genes Cells 10: 963–972.

Onai, K., Okamoto, K., Nishimoto, H., Morioka, C., Hirano, M., Kamiike, N. et al. (2004) Large-scale screening of Arabidopsis circadian clock mutants by a high-throughput real-time bioluminescence monitoring system. Plant J. 40: 1–11.

Panda, S., Poirier, G.G. and Kay, S.A. (2002) tef defines a role for poly(ADP-ribosyl)ation in establishing period length of the Arabidopsis circadian oscillator. Dev. Cell 3: 51–61.

Para, A., Farre, E.M., Imaizumi, T., Pruneda-Paz, J.L., Harmon, F.G. and Kay, S.A. (2007) PRR3 is a vascular regulator of TOC1 stability in the Arabidopsis circadian clock. Plant Cell 19: 3462–3473.

Park, D.H., Somers, D.E., Kim, Y.S., Choy, Y.H., Lim, H.K., Soh, M.S. et al. (1999) Control of circadian rhythms and photoperiodic flowering by the Arabidopsis GIGANTEA gene. Science 285: 1579–1582.

Penfield, S. and Hall, A. (2009) A role for multiple circadian clock genes in the response to signals that break seed dormancy in Arabidopsis. Plant Cell 21: 1722–1732.

Perales, M. and Mas, P. (2007) A functional link between rhythmic changes in chromatin structure and the Arabidopsis biological clock. Plant Cell 19: 2111–2123.

Perales, M., Portoles, S. and Mas, P. (2006) The proteasome-dependent degradation of CK84 is regulated by the Arabidopsis biological clock. Plant J. 46: 849–860.

Pittendrigh, C.S. (1993) Temporal organization: reflections of a Darwinian clock-watcher. Annu. Rev. Physiol. 55: 16–54.

Pruneda-Paz, J.L., Breton, G., Para, A. and Kay, S.A. (2009) A functional genomics approach reveals CHE as a component of the Arabidopsis circadian clock. Science 323: 1481–1485.

Raser, J.M. and O'Shea, E.K. (2005) Noise in gene expression: origins, consequences, and control. Science 309: 1602–1609.

Rawat, R., Schwartz, J., Jones, M.A., Sairinen, I., Cheng, Y., Andersson, C.R. et al. (2009) REV14L1, a Myb-like transcription factor, integrates the circadian clock and auxin pathways. Proc. Natl Acad. Sci. USA 106: 16883–16888.

Rawat, R., Takahashi, N., Hsu, P.Y., Jones, M.A., Schwartz, J., Salem, M.R. et al. (2011) REV14L1 and PSEUDO-RESPONSE REGULATORS form a negative feedback loop within the Arabidopsis circadian clock. PLoS Genet. 7: e1001350.

Salome, P.A. and McClung, C.R. (2005) PSEUDO-RESPONSE REGULATOR 7 and 9 are partially redundant genes essential for the temperature responsiveness of the Arabidopsis circadian clock. Plant Cell 17: 791–803.

Salome, P.A., Weigel, D. and McClung, C.R. (2010) The role of the Arabidopsis morning loop components CCA1, LHY, PRR7, and PRR9 in temperature compensation. Plant Cell 22: 3650–3661.

Sanchez, S.E., Petriillo, E., Beckwith, E.J., Zhang, X., Rugnone, M.L., Hernando, C.E. et al. (2010) A methyl transferase links the circadian clock to the regulation of alternative splicing. Nature 466: 112–116.
Sato, E., Nakamichi, N., Yamashino, T. and Mizuno, T. (2002) Aberrant expression of the Arabidopsis circadian-regulated APRR5 gene belonging to the APRR1/TOC1 quintet results in early flowering and hypersensitivity to light in early photomorphogenesis. Plant Cell Physiol. 43: 1374–1385.

Sawa, M., Nusinow, D.A., Kay, S.A. and Imaizumi, T. (2007) FKFI1 and GIGANTEA complex formation is required for day-length measurement in Arabidopsis. Science 318: 261–265.

Schaffer, R., Ramsay, N., Samach, A., Corden, S., Putterill, J., Carre, I.A. et al. (1998) The late elongated hypocotyl mutation of Arabidopsis disrupts circadian rhythms and the photoperiodic control of flowering. Cell 93: 1219–1229.

Schultz, T.F., Kiyosue, T., Yanovsky, M., Wada, M. and Kay, S.A. (2001) A role for LKP2 in the circadian clock of Arabidopsis. Plant Cell 13: 2659–2670.

Seriakawa, M., Miwa, K., Kondo, T. and Oyama, T. (2008) Functional conservation of clock-related genes in flowering plants: overexpression and RNA interference analyses of the circadian rhythm in the monocotyledon Lemna gibba. Plant Physiol. 146: 1952–1963.

Somers, D.E., Schultz, T.F., Milnamow, M. and Kay, S.A. (2000) ZEITLUPE encodes a novel clock-associated PAS protein from Arabidopsis. Cell 101: 319–329.

Somers, D.E., Webb, A.A., Pearson, M. and Kay, S.A. (1998) The short-period mutant, toc1-1, alters circadian clock regulation of multiple outputs throughout development in Arabidopsis thaliana. Development 125: 485–494.

Song, Y.H., Ito, S. and Imaizumi, T. (2010) Similarities in the circadian clock and photoperiodism in plants. Curr. Opin. Plant Biol. 13: 594–603.

Strayer, C., Oyama, T., Schultz, T.F., Raman, R., Somers, D.E., Mas, P. et al. (2000) Cloning of the Arabidopsis clock gene TOC1, an auto-regulatory response regulator homolog. Science 289: 768–771.

Sugano, S., Andronis, C., Green, R.M., Wang, Z.Y. and Tobin, E.M. (1998) Protein kinase CK2 interacts with and phosphorylates the Arabidopsis clock-cassociated 1 protein. Proc. Natl Acad. Sci. USA 95: 11020–11025.

Sugano, S., Andronis, C., Ong, M.S., Green, R.M. and Tobin, E.M. (1999) The protein kinase CK2 is involved in regulation of circadian rhythms in Arabidopsis. Proc. Natl Acad. Sci. USA 96: 12362–12366.

Takase, T., Ishikawa, H., Murakami, H., Kikuchi, J., Sato-Nara, K. and Suzuki, H. (2011) The circadian clock modulates water dynamics and aquaporin expression in Arabidopsis roots. Plant Cell Physiol. 52: 373–383.

Thain, S.C., Vandenbussche, F., Laarhoven, L.J., Dowson-Day, M.J., Wang, Z.Y., Tobin, E.M. et al. (2004) Circadian rhythms of ethylene emission in Arabidopsis. Plant Physiol. 136: 3751–3761.

Tiwari, S.B., Shen, Y., Chang, H.C., Hou, Y., Harris, A., Ma, S.F. et al. (2010) The flowering time regulator CONSERVATION OF circadian rhythms is required for the FLOWERING LOCUS T promoter via a unique cis-element. New Phytol. 187: 57–66.

Tomita, J., Nakajima, M., Kondo, T. and Iwasaki, H. (2005) No transcription–translation feedback in circadian rhythm of KaiC phosphorylation. Science 307: 251–254.

Turner, A., Beales, J., Faure, S., Dunford, R.P. and Laurie, D.A. (2005) The pseudo-response regulator Ppd-H1 provides adaptation to photo-period in barley. Science 310: 1031–1034.

Wang, L., Fujikawa, S. and Somers, D.E. (2010) PRR5 regulates phosphorylation, nuclear import and subnuclear localization of TOC1 in the Arabidopsis circadian clock. EMBO J. 29: 1903–1915.

Wang, W., Barnaby, J.Y., Tada, Y., Li, H., Tor, M., Caldelari, D. et al. (2011) Timing of plant immune responses by a central circadian regulator. Nature 470: 110–114.

Wang, Y., Wu, J.F., Nakamichi, N., Sakakibara, H., Nam, H.G. and Wu, S.H. (2011) LIGHT-REGULATED WD1 and PSEUDO-RESPONSE REGULATOR9 form a positive feedback regulatory loop in the Arabidopsis circadian clock. Plant Cell 23: 486–498.

Wang, Z.Y., Kenigsbuch, D., Sun, L., Harel, E., Ong, M.S. and Tobin, E.M. (1997) A Myb-related transcription factor is involved in the phytochrome regulation of an Arabidopsis Lhcb gene. Plant Cell 9: 491–507.

Wang, Z.Y. and Tobin, E.M. (1998) Constitutive expression of the CIRCADIAN CLOCK ASSOCIATED 1 (CCA1) gene disrupts circadian rhythms and suppresses its own expression. Cell 93: 1207–1217.

Warren, D.M. and Wilkins, M.B. (1961) An endogenous rhythm in the rate of dark-fixation of carbon dioxide in leaves of Bryophyllum fedtschenkoi. Nature 191: 686–688.

Wenkel, S., Turck, F., Singer, K., Gisot, L., Le Gourrierec, J., Samach, A. et al. (2006) CONSTANS and the CCAAT box binding complex share a functionally important domain and interact to regulate flowering of Arabidopsis. Plant Cell 18: 2971–2984.

Wu, J.F., Wang, Y. and Wu, S.H. (2008) Two new clock proteins, LWD1 and LWD2, regulate Arabidopsis photoperiodic flowering. Plant Physiol. 148: 948–959.

Xu, X., Hotta, C.T., Dodd, A.N., Love, J., Sharrock, R., Lee, Y.W. et al. (2007) Distinct light and clock modulation of cytosolic free Ca2+ oscillations and rhythmic CHLOROPHYLL A/B BINDING PROTEIN2 promoter activity in Arabidopsis. Plant Cell 19: 3474–3490.

Yamamoto, Y., Sato, E., Shimizu, T., Nakamichi, N., Sato, S., Kato, T. et al. (2003) Comparative genetic studies on the APRR5 and APRR7 genes belonging to the APRR1/TOC1 quintet implicated in circadian rhythm, control of flowering time, and early photomorphogenesis. Plant Cell Physiol. 44: 1119–1130.

Yazdanbakhsh, N., Sulpice, R., Graf, A., Stitt, M. and Fisahn, J. (2011) Circadian control of root elongation and C partitioning in Arabidopsis thaliana. Plant Cell Environ. 34: 877–894.

Yerushalmi, S., Yakir, E. and Green, R.M. (2011) Circadian clocks and adaptation in Arabidopsis. Mol. Ecol. 20: 1155–1165.

Zhang, X., Chen, Y., Wang, Z.Y., Chen, Z., Gu, H. and Qu, L.J. (2007) Constitutive expression of CIR1 (RVE2) affects several circadian-regulated processes and seed germination in Arabidopsis. Plant J. 51: 512–525.