The Root Growth-Regulating Brevicompanine Natural Products Modulate the Plant Circadian Clock

Amaury de Montaigu,[†,∇,○] Julian Oeljeklaus,[‡,∇] Jan H. Krahn,[‡] Mohamed N.S. Suliman,[§] Vivek Halder,[‡,§] Elisa de Ansorena,[†] Sabrina Nickel,[‡] Markus Schlicht,[§] Ondřej Plíhal,[∥] Karolina Kubiasová,[∥] Lenka Radová,[⊥] Barbara Kracher,[#] Réka Tóth,[†,◆] Farnusch Kaschani,[‡] George Coupland,[†] Erich Kombrink,[§] and Markus Kaiser*,[‡]

[†]Department of Developmental Biology, Max-Planck-Institute for Plant Breeding Research, Carl-von-Linné-Weg 10, 50829 Köln, Germany

[‡]Department of Chemical Biology, Universität Duisburg-Essen, ZMB, Faculty of Biology, Universitätsstr. 2, 45117 Essen, Germany

[§]Chemical Biology Laboratory, Max-Planck-Institute for Plant Breeding Research, Carl-von-Linnè-Weg 10, 50829 Köln, Germany

[∥]Department of Molecular Biology, Centre of the Region Haná for Biotechnological and Agricultural Research, Palacký University, Šlechtitelů 241/27, 78371 Olomouc, Czech Republic

[⊥]Center of Molecular Medicine, Central European Institute of Technology, Masaryk University, Kamenice 753/5, 62500 Brno, Czech Republic

[#]Bioinformatics, Department of Plant Microbe Interactions, Max-Planck-Institute for Plant Breeding Research, Carl-von-Linnè-Weg 10, 50829 Köln, Germany

S *Supporting Information*

ABSTRACT: Plant growth regulating properties of brevicompanines (Brvs), natural products of the fungus *Penicillium brevicompactum*, have been known for several years, but further investigations into the molecular mechanism of their bioactivity have not been performed. Following chemical synthesis of brevicompanine derivatives, we studied their activity in the model plant *Arabidopsis* by a combination of plant growth assays, transcriptional profiling, and numerous additional bioassays. These studies demonstrated that brevicompanines cause transcriptional misregulation of core components of the circadian clock, whereas other biological read-outs were not affected. Brevicompanines thus represent promising chemical tools for investigating the regulation of the plant circadian clock. In addition, our study also illustrates the potential of an unbiased -omics-based characterization of bioactive compounds for identifying the often cryptic modes of action of small molecules.
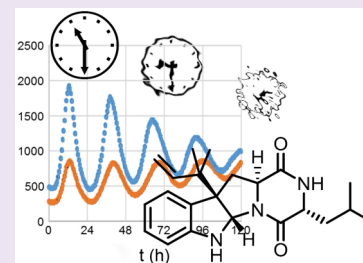
Natural products have a long-standing history as starting points for the development of chemical probes.[1] In the plant sciences, this approach has been less frequently used, although the need for chemical probes with interesting biological activities has recently been recognized.[2,3] Accordingly, the number of examples of natural product-derived chemical probes in plant systems is still limited.[4]

The natural product class of brevicompanines (consisting of BrvA–BrvC, Figure 1a) were isolated from the culture filtrate of the fungus *Penicillium brevicompactum* and found to display plant growth regulating properties.[5,6] Chemically, brevicompanines are diketopiperazine derivatives of the larger hexahydro pyrroloindolo[2,3-*b*] (HPI) natural product family, with the particular feature of containing a (D)-configured amino acid residue as part of their diketopiperazine moiety and a reverse prenyl residue at the HPI core. Intriguingly, they displayed differential biological activities in different plant species. In lettuce (*Lactuca sativa*) seedlings, they promoted root growth in a dose-dependent manner, whereas in rice (*Oryza sativa*), at the same concentrations, no such effect was observed.[5,6] The

molecular mechanism underlying the root growth modulating activity however remains unknown so far. Moreover, the biological activities of brevicompanines in other plants, in particular the model plant *Arabidopsis* (*Arabidopsis thaliana*), have not yet been determined, thereby limiting a potential application of brevicompanines in plant chemical biology research. Accordingly, we here describe a molecular analysis of the bioactivity of brevicompanines in *Arabidopsis*. These investigations revealed that brevicompanines selectively attenuate the oscillation of the plant circadian clock.
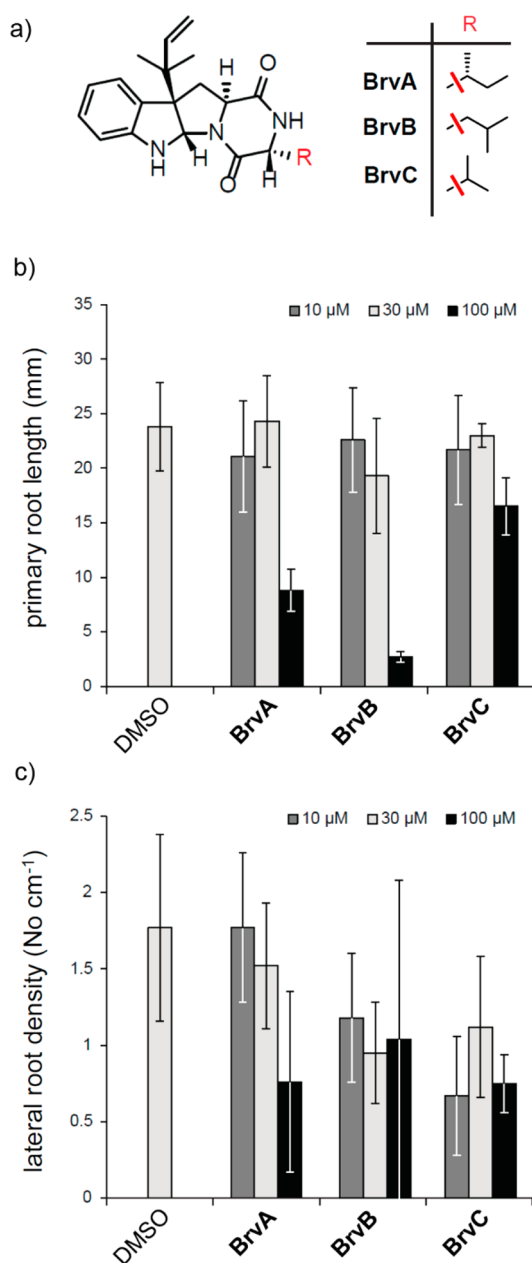
■ RESULTS AND DISCUSSION

We chemically synthesized the three major naturally occurring brevicompanine derivatives (BrvA–BrvC, Figure 1a), following essentially established synthesis protocols (Supporting Information).[7] We then first investigated their impact on

Figure 1. Root growth effects of Brevicompanines in *Arabidopsis*. (a) Chemical structure of the natural products brevicompanine A–C (BrvA–BrvC) used in this study. (b) Primary root length, and (c) lateral root density of *Arabidopsis* (Col-0) seedlings 10 days after germination in the presence of varying concentrations of BrvA–BrvC. Error bars indicate the standard deviation of at least three independent experiments.

Arabidopsis root development and found that all three brevicompanines at 100 μM generally inhibit primary growth (root length) and secondary growth (lateral root density) in a differential and dose-dependent manner (Figure 1b and c). BrvA and BrvB (at 100 μM) effectively inhibited primary root growth, whereas BrvC had only a small effect. In contrast, secondary growth (lateral root density) was equally impaired by all compounds, even at low concentrations (10–30 μM, Figure 1b and c). We therefore conclude that brevicompanines display differential effects on *Arabidopsis* root growth with BrvB as the most active compound, whereas BrvC displayed the strongest selectivity.

In order to gain an unbiased insight into the molecular responses caused by brevicompanine treatment, we next performed a microarray-based gene expression study. For this analysis, we focused on BrvC because of its selective bioactivity. We analyzed gene expression after a short (6 h) and long (48 h) exposure to 50 μM BrvC to monitor rapid and continuous responses (Figure 2a, both time intervals refer to the same starting time, which was 10 am, 2 h after lights-on). The short-term treatment (6 h) resulted in significant reprogramming of gene transcription in comparison to DMSO-treated plants, yielding 1317 and 867 signature sequences in annotated genes that were up- and downregulated with |log$_2$ FC| $\geq$ 1, respectively (for $P \leq 0.001$, Supporting Table 1). The changes of the expression profile after long-term treatment (48 h) with BrvC were less severe (Supporting Table 1), but most of the significantly altered genes were unidirectionally up- or down-regulated at both time points (Figure 2a and b).

Subsequently, we focused our analysis on those genes that were significantly up- or downregulated at both time points because these genes may best reflect a potential "chemical gene knockout" underlying the bioactivity of BrvC. Accordingly, we ranked all genes that were upregulated after 6 and 48 h with log$_2$ FC $\geq$ 2.0 (for $P \leq 0.001$, Supporting Table 2) or that were downregulated after 6 and 48 h with log$_2$ FC $\leq$ −2.0 (for $P \leq$ 0.001, Supporting Table 3). Thorough analysis of these data revealed that the BrvC treatment affected the transcription of core component genes of the plant circadian clock.[8] These genes are responsible for generating and maintaining the approximately 24-h rhythm and display characteristic oscillating expression patterns peaking at a distinct time of the day. BrvC application downregulated the expression of the morning clock component genes *CIRCADIAN CLOCK ASSOCIATED 1* (*CCA1*), *LATE ELONGATED HYPOCOTYL* (*LHY*), *REVEILLE8* (*RVE8*), and *REVEILLE4* (*RVE4*) and upregulated the expression of the evening genes *PSEUDO-RESPONSE REGULATOR 3* (*PRR3*) and *TIMING OF CAB EXPRESSION 1* (*TOC1*; Figure 2c).

Additionally, our analysis also revealed the downregulation of *NIGHT LIGHT-INDUCIBLE AND CLOCK-REGULATED GENE 2 and 1* (*LNK2* and *LNK1*), which are also implicated in the regulation of the circadian clock, although the underlying molecular mechanism is only partially understood.[8] As the circadian clock is known to act as a major regulator of gene transcription, affecting the expression of ~30% of all plant genes,[8–10] many additional genes that we identified as significantly changed in our microarray analysis are regulated by the circadian clock (e.g., *NIGHT LIGHT-INDUCIBLE AND CLOCK-REGULATED GENE 3* (*LNK3*) or the *CYCLING DOF FACTOR 1, 2 and 3* (*CDF1*, *CDF2*, and *CDF3*, Supporting Table 2 and Supporting Table 3)).

Next, we tested whether the exposure of *Arabidopsis* seedlings to brevicompanines indeed has an effect on circadian rhythms by monitoring the expression of the well-characterized circadian marker *GIGANTEA::LUCIFERASE* (*GI::LUC*), which is known to show robust and synchronized rhythms under a variety of conditions and was previously used in a chemical screen for compounds that alter plant circadian rhythms.[11] Initially, we assessed the effect of brevicompanines on *GI::LUC* expression in constant darkness (DD), when the circadian rhythm is uncoupled from the modifying effects of light. Under these conditions, application of BrvC significantly reduced the circadian amplitude (half of the difference between peak and trough, hereafter called "amplitude") of *GI::LUC*
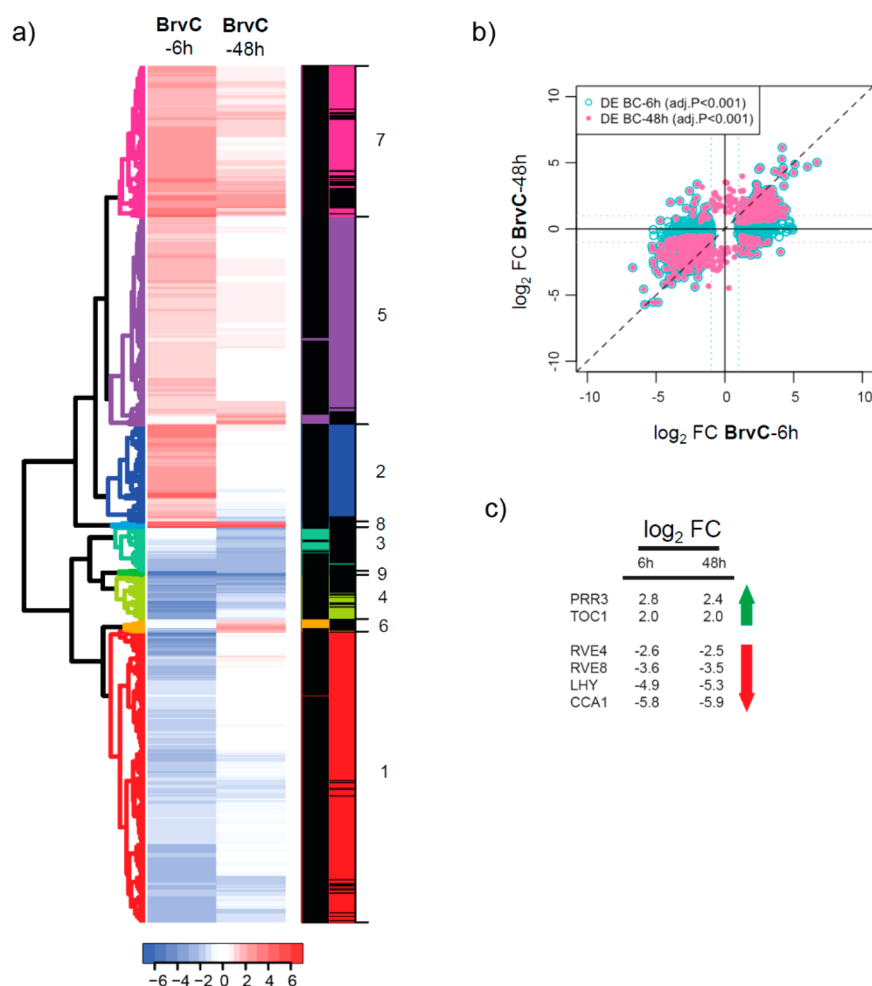
Figure 2. Impact of BrvC treatment on circadian clock genes in *Arabidopsis* revealed by DNA microarray-based transcriptional analysis. A microarray-based gene expression analysis of *Arabidopsis* (Col-0) plants was performed after 6 and 48 h treatment with 50 μM BrvC. (a) Clustered heatmap visualization of log$_2$ fold changes for all genes that were significantly differentially expressed with |log$_2$ FC| $\geq$ 1 and P < 0.001. Genes were clustered using complete-linkage hierarchical clustering, and clusters of genes with similar expression patterns are uniformly colored. (b) Scatter plot comparing the observed log$_2$ fold change values of all differentially expressed genes (with P < 0.001) after 6 h (x-axis) and 48 h (y-axis). The filled magenta-colored circles indicate genes with P < 0.001 at 48 h, while the turquoise-colored rings indicate genes with P < 0.001 at 6 h. (c) List of genes that displayed a unidirectional |log$_2$ FC| $\geq$ 2 for the 6 and 48 h time-point and are known to function primarily in the plant circadian clock.[8]

expression in a dose-dependent manner (Figure 3a). In order to assess whether this effect was caused by a specific molecular interaction of BrvC with a target, we chemically synthesized D-BrvC, the (D)-isomer of BrvC (for chemical structure, see Supporting Information Figure 1; chemical synthesis is described in the Supporting Information). In contrast to BrvC, D-BrvC did not significantly affect the amplitude of *GI::LUC* rhythms, thus indicating a specific effect of BrvC (Figure 3b).

We next evaluated the impact of BrvB on the circadian rhythm as BrvB is commercially available (thereby facilitating future application as a chemical research tool) and overall displayed the highest inhibition of plant root growth. Exposure of *Arabidopsis* seedlings to BrvB (100 μM) reduced the amplitude of rhythmic *GI::LUC* expression in DD but, in contrast to BrvC, also increased the circadian period length (duration of the circadian cycle, hereafter called "period"; Figure 3c and Supporting Figure 2a). More detailed analyses revealed that BrvB exerted its effects on the amplitude and period length of rhythmic *GI::LUC* expression in a dose-dependent manner (Figure 3d). In a similar fashion, BrvB also

affected the amplitude and period length of the rhythmic expression of *CCA1::LUC*, another well-established circadian marker that is also a core component of the circadian oscillator (Supporting Figure 2b). Notably, the rhythm of *CCA1* expression in DD dampened faster than that of *GI*, which may explain why the effects of BrvB on this marker were less consistent across experiments.[11]

Finally, we extended the analysis of brevicompanines on circadian rhythms to include constant light (LL) conditions and essentially confirmed the bioactivities of BrvB and BrvC and the inactivity of D-BrvC. As previously seen under DD conditions, BrvB also reduced the amplitude and lengthened the period of the oscillating *GI::LUC* and *CCA1::LUC* expression, whereas BrvC only affected the amplitude and D-BrvC was inactive (Figure 3e and f and Supporting Figure 3). Taken together, these results indicate that brevicompanines alter the rhythmic amplitude of two core components of the circadian oscillator under DD and LL conditions, thus demonstrating that these chemicals are modulators of the circadian clock. The selective bioactivity of BrvC on the amplitude over the period of the oscillation contrasted with the more general effect of BrvB, an
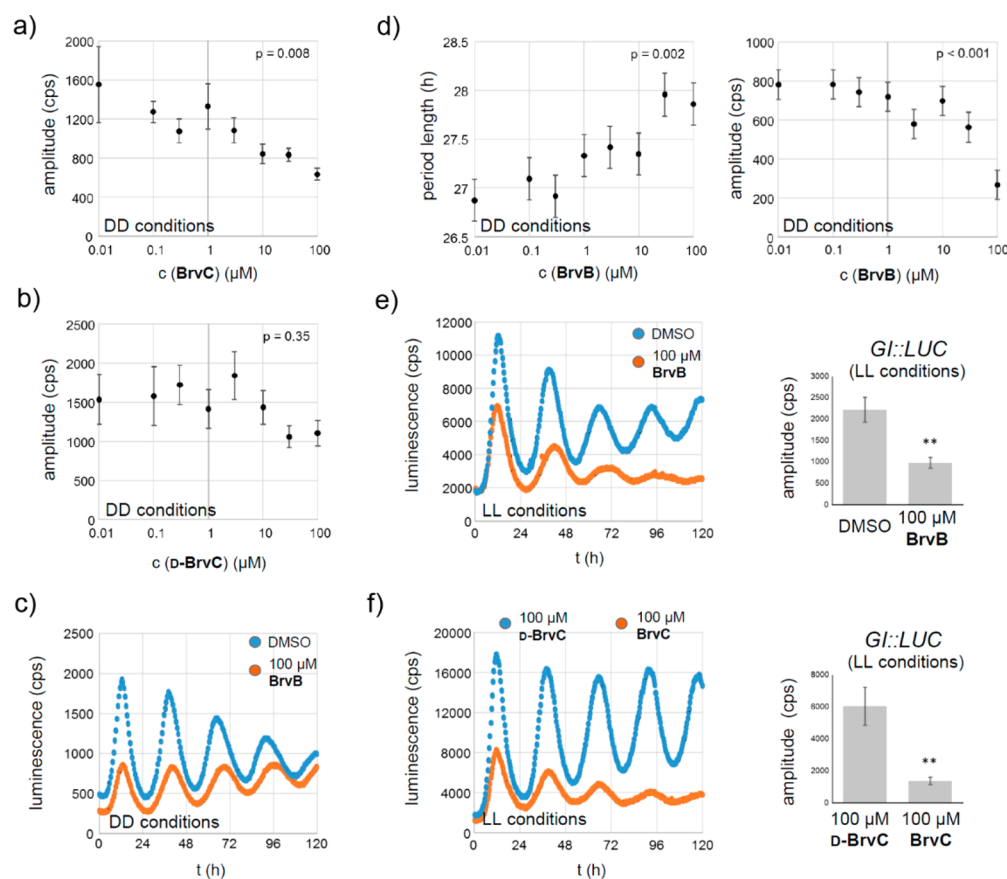
Figure 3. Modulation of plant circadian rhythms by brevicompanines. (a) Amplitude of *GI::LUC* rhythms in response to increasing concentrations of BrvC under constant darkness (DD) conditions. Data are the means of two biological replicates, with 12 individuals per replicate. The *p* value (*p*) was determined with a two-way ANOVA using concentration and experiment as factors and indicates a significant effect of BrvC on amplitude (α = 0.05). (b) Amplitude of *GI::LUC* rhythms in response to increasing concentrations of D-BrvC under constant darkness (DD) conditions. Statistics was performed as described in a. (c) Waveform of *GI::LUC* activity in constant darkness (DD) after exposure to 100 μM BrvB (orange curve) or DMSO (blue curve); *n* = 12. (d) Period (left panel) and amplitude (right panel) of *GI::LUC* rhythms in response to increasing concentrations of BrvB in constant darkness (DD). Statistics was performed as described in a. (e) Waveform of *GI::LUC* activity in constant light (LL) after exposure to 100 μM BrvB (orange curve) or DMSO (blue curve; left panel) and corresponding amplitude of *GI::LUC* rhythms in constant light (LL; right panel); *n* = 12. Statistical difference from the DMSO control was determined with a Student's *t* test (α = 0.05; *P < 0.05, **P < 0.001). (f) Waveform of *GI::LUC* activity in constant light (LL) after exposure to 100 μM BrvC (orange curve) or 100 μM D-BrvC (blue curve; left panel) and corresponding amplitude of *GI::LUC* rhythms in LL (right panel); *n* = 12. Statistics were performed as described in e. In all experiments, seedlings bearing the *GI::LUC* reporter were entrained for 7 days in day/night regimes of 16 h light/8 h dark. Seedlings were then transferred on day 7 to 96-well plates containing solid medium supplied with chemicals at the indicated concentrations. The resulting luminescence signals were measured over 5 days. In all panels, amplitude and raw luminescence are expressed in counts per second (cps), and period length is expressed in hours (h).

observation that parallels the results obtained with the root growth assays. Amplitude and period length are regulated by different molecular mechanisms in animals,[12] and BrvC might therefore be used in future studies as a tool to study specific physiological effects of amplitude variation in plants.

The circadian clock controls root growth, and brevicompanines control both the clock and root elongation (Figures 1−3).[13] The regulation of circadian rhythms and of root elongation could be two independent functions of brevicompanines, but there is also the possibility that brevicompanines control root growth by modulating the regulation of central components of the oscillator (Figures 2 and 3). To this end, we first confirmed that the inactive enantiomer of BrvC, D-BrvC, had no effect on primary root elongation in the Col-0 WT (Figure 4a). We then performed experiments to exclude that brevicompanines were altering root growth by acting on hormone signaling pathways. Root growth and development is controlled by several plant hormones (auxin, cytokinins, abscisic acid, and others)[14] and particularly auxin functions as

a critical regulator of lateral root formation.[15] Accordingly, we monitored the effect of BrvB on various reporter genes that selectively respond to different plant hormones. To this end, we used transgenic *Arabidopsis* lines expressing (i) the *DR5p::GUS* reporter, which is frequently used to monitor alterations in auxin levels,[16] (ii) the *ARR5p::GUS* reporter as a proxy of altered cytokinin levels,[17] (iii) the *DC3p::GUS* reporter responsive to abscisic acid (ABA),[18] and (iv) the jasmonate-responsive *VSP1::GUS* reporter.[19] None of these reporters were strongly affected in their expression upon treatment with BrvB, i.e., neither induced in the absence of the corresponding phytohormones nor impaired by its presence, suggesting that endogenous hormone levels (auxin, cytokinin, ABA, or jasmonate signaling) are not affected and therefore do not cause the observed root phenotype (Supporting Figure 4). Instead, the modulation of root growth by brevicompanines might be mediated by changes in the expression of circadian clock genes induced by the application of these chemicals.
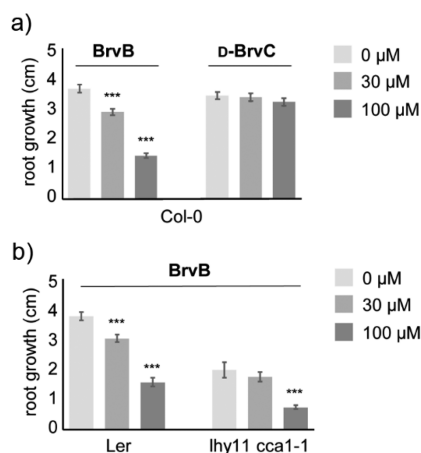
Figure 4. Requirement of LHY and CCA1 activity for the inhibition of root growth by BrvB. (a) Primary root length of *Arabidopsis* (Col-0) seedlings exposed to the indicated concentrations of BrvB and D-BrvC. Between 8 and 11 seedlings were used per treatment. (b) Primary root length of the *lhy11 cca1−1* double mutant and of the Ler control after exposure to BrvB at the indicated concentrations. The data were obtained from two biological replicates. Twelve to 26 seedlings were used per genotype and condition. Error bars indicate the standard error of the mean. Statistical difference from the DMSO control was determined with a Student's *t* test ($\alpha = 0.05$; ***$P < 0.001$).

The functionally redundant genes *LHY* and *CCA1* are central components of the oscillator and are the two circadian clock genes most strongly misregulated by the application of BrvC (Figure 2).[20] *LHY* and *CCA1* are expressed in roots,[21] and their activity is essential for the oscillator to generate sustained rhythms not only in the shoots but also in the roots.[22] Importantly, the analysis of loss of function mutants demonstrated that LHY and CCA1 promote root growth by acting at certain times of the diel cycle.[13] Loss of function of other central circadian clock genes such as *EARLY FLOWERING 3* and *4* (*ELF3* and *ELF4*) also affects root growth. But, the rhythmic pattern of root growth differs between clock mutants,[23] and *ELF3* and *ELF4* expression levels are not strongly affected by the application of BrvC (Supporting Table 1). These observations suggested that brevicompanines might modulate root growth by altering the expression of *LHY* and *CCA1*. Along these lines, we determined primary root length after application of BrvB in the *lhy11 cca1−1* double mutant as well as in the *elf3−1* and *elf4−101* loss of function mutants.[20] These experiments revealed the general tendency of a reduced effect of BrvB in the *lhy11 cca1−1* mutant (Figure 4b) but not in the *elf3−1* and *elf4−101* mutants (Supporting Figure 5). In fact, statistical analyses (ANOVA) supported the *lhy11 cca1−1* genotype limiting the effect of BrvB on root growth (significant genotype × treatment interaction with $P = 0.013$ for the 30 μM treatment and $P < 0.001$ for the 100 μM treatment). On the basis of these results, we propose that brevicompanines repress root growth at least partly by repressing the expression of *LHY* and *CCA1*, two central components of the circadian clock.

Overall, we conclude that BrvB displays apparent selectivity by modulating only the circadian clock but induces no other tested biological responses in plants. Notwithstanding differences in activity between BrvB and BrvC, the results generally converge on brevicompanines predominantly regulating the amplitude of the rhythm rather than the period length. The molecular basis of the different bioactivity of the structurally rather similar compounds BrvB and BrvC is unknown and

could be caused by different factors such as different binding affinities to their protein target(s) or different pharmacokinetic properties including differential uptake, metabolism, and distribution in distinct plant tissues. As BrvB is commercially available, we anticipate that it may represent a versatile chemical tool for studying the molecular regulation of the plant circadian clock, *e.g.*, in combinatorial chemical genetics approaches that may complement the currently popular genetic studies in the plant field.[24] Of note, brevicompanines fill a gap in the current chemical tool repertoire. In contrast to small molecule modulators of the mammalian circadian clock, *e.g.*, the CRY stabilizers KL001 (and derivatives thereof) or the kinase inhibitor longdaysin,[23,25−28] only one plant circadian clock modulator, the actin stabilizer prieurianin/endosidin 1,[11] has been reported so far. This compound, however, is difficult to use due to its indirect mode of action. Unfortunately, the direct target(s) of the brevicompanines have remained elusive so far and require further experiments. We anticipate that a systematic screening of clock mutants or biochemical approaches such as affinity purifications with chemically modified brevicompanines might represent suitable approaches to identify their enigmatic target protein(s).

Our studies furthermore indicate that the observed root growth phenotype is at least partly mediated by alterations in the expression level of two circadian clock components, although further investigations into this direction are still required. This phenotype thus joins a growing number of various growth phenotypes or effects such as heterosis that are known to be induced by a deregulated circadian clock.[5,8,29,30]

Finally, our study highlights the potential of unbiased -omics-based approaches to decipher cryptic bioactivities of natural products. We believe that with the advances in the systematic analysis of such data, this approach will become an established methodology to unravel bioactivities of small molecules.[31]

■ METHODS

Chemical synthesis and experimental procedures are included in the Supporting Information.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acschembio.6b00978.

Supporting figures, supporting procedures and methods, and supporting references (PDF)
Supporting Table 1 (PDF)
Supporting Table 2 (PDF)
Supporting Table 3 (PDF)

■ AUTHOR INFORMATION

Corresponding Author
*E-mail: markus.kaiser@uni-due.de.

ORCID
Markus Kaiser: 0000-0002-6540-8520

Present Addresses
○Institute for Quantitative Genetics and Genomics of Plants, Heinrich-Heine-University, 40225 Düsseldorf, Germany
◆Department of Plant Sciences, University of Oxford, South Parks Road, Oxford, OX1 3RB, United Kingdom

Author Contributions

∇Both authors contributed equally.

Notes

The authors declare no competing financial interest.

■ REFERENCES

(1) Carlson, E. E. (2010) Natural products as chemical probes. *ACS Chem. Biol. 5*, 639−653.

(2) Hicks, G. R., and Raikhel, N. V. (2009) Opportunities and challenges in plant chemical biology. *Nat. Chem. Biol. 5*, 268−272.

(3) Hicks, G. R., and Raikhel, N. V. (2014) Plant chemical biology: are we meeting the promise? *Front. Plant Sci. 5*, DOI: 10.3389/fpls.2014.00455.

(4) Hicks, G. R., and Raikhel, N. V. (2012) Small molecules present large opportunities in plant biology. *Annu. Rev. Plant Biol. 63*, 261−282.

(5) Kusano, M., Sotoma, G., Koshino, H., Uzawa, J., Chijimatsu, M., Fujioka, S., Kawano, T., and Kimura, Y. (1998) Brevicompanines A and B: new plant growth regulators produced by the fungus, Penicillium brevicompactum. *J. Chem. Soc., Perkin Trans. 1 1*, 2823−2826.

(6) Kimura, Y., Sawada, A., Kuramata, M., Kusano, M., Fujioka, S., Kawano, T., and Shimada, A. (2005) Brevicompanine C, cyclo-(D-Ile-L-Trp), and cyclo-(D-Leu-L-Trp), plant growth regulators from Penicillium brevi-compactum. *J. Nat. Prod. 68*, 237−239.

(7) Matsumura, K., and Kitahara, T. (2001) Synthesis of brevicompanines, plant growth regulators. *Heterocycles 54*, 727−734.

(8) Hsu, P. Y., and Harmer, S. L. (2014) Wheels within wheels: the plant circadian system. *Trends Plant Sci. 19*, 240−249.

(9) Greenham, K., and McClung, C. R. (2015) Integrating circadian dynamics with physiological processes in plants. *Nat. Rev. Genet. 16*, 598−610.

(10) Harmer, S. L. (2009) The circadian system in higher plants. *Annu. Rev. Plant Biol. 60*, 357−377.

(11) Toth, R., Gerding-Reimers, C., Deeks, M. J., Menninger, S., Gallegos, R. M., Tonaco, I. A., Hubel, K., Hussey, P. J., Waldmann, H., and Coupland, G. (2012) Prieurianin/endosidin 1 is an actin-stabilizing small molecule identified from a chemical genetic screen for circadian clock effectors in Arabidopsis thaliana. *Plant J. 71*, 338−352.

(12) Zhao, X., Hirota, T., Han, X., Cho, H., Chong, L. W., Lamia, K., Liu, S., Atkins, A. R., Banayo, E., Liddle, C., Yu, R. T., Yates, J. R., 3rd, Kay, S. A., Downes, M., and Evans, R. M. (2016) Circadian Amplitude Regulation via FBXW7-Targeted REV-ERBalpha Degradation. *Cell 165*, 1644−1657.

(13) 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.

(14) Santner, A., and Estelle, M. (2009) Recent advances and emerging trends in plant hormone signalling. *Nature 459*, 1071−1078.

(15) Lavenus, J., Goh, T., Roberts, I., Guyomarc'h, S., Lucas, M., De Smet, I., Fukaki, H., Beeckman, T., Bennett, M., and Laplaze, L. (2013) Lateral root development in Arabidopsis: fifty shades of auxin. *Trends Plant Sci. 18*, 450−458.

(16) Ulmasov, T., Murfett, J., Hagen, G., and Guilfoyle, T. J. (1997) Aux/IAA proteins repress expression of reporter genes containing natural and highly active synthetic auxin response elements. *Plant Cell 9*, 1963−1971.

(17) Romanov, G. A., Kieber, J. J., and Schmulling, T. (2002) A rapid cytokinin response assay in Arabidopsis indicates a role for phospholipase D in cytokinin signalling. *FEBS Lett. 515*, 39−43.

(18) Chak, R. K., Thomas, T. L., Quatrano, R. S., and Rock, C. D. (2000) The genes ABI1 and ABI2 are involved in abscisic acid- and drought-inducible expression of the Daucus carota L. Dc3 promoter in guard cells of transgenic Arabidopsis thaliana (L.) Heynh. *Planta 210*, 875−883.

(19) Meesters, C., Monig, T., Oeljeklaus, J., Krahn, D., Westfall, C. S., Hause, B., Jez, J. M., Kaiser, M., and Kombrink, E. (2014) A chemical inhibitor of jasmonate signaling targets JAR1 in Arabidopsis thaliana. *Nat. Chem. Biol. 10*, 830−836.

(20) Mizoguchi, T., Wheatley, K., Hanzawa, Y., Wright, L., Mizoguchi, M., Song, H. R., Carre, I. A., and Coupland, G. (2002) LHY and CCA1 are partially redundant genes required to maintain circadian rhythms in Arabidopsis. *Dev. Cell 2*, 629−641.

(21) Bouche, F., D'Aloia, M., Tocquin, P., Lobet, G., Detry, N., and Perilleux, C. (2016) Integrating roots into a whole plant network of flowering time genes in Arabidopsis thaliana. *Sci. Rep. 6*, 29042.

(22) James, A. B., Monreal, J. A., Nimmo, G. A., Kelly, C. L., Herzyk, P., Jenkins, G. I., and Nimmo, H. G. (2008) The circadian clock in Arabidopsis roots Is a simplified slave version of the clock in shoots. *Science 322*, 1832−1835.

(23) Hirota, T., and Kay, S. A. (2009) High-throughput screening and chemical biology: New approaches for understanding circadian clock mechanisms. *Chem. Biol. 16*, 921−927.

(24) Lehàr, J., Stockwell, B. R., Giaever, G., and Nislow, C. (2008) Combination chemical genetics. *Nat. Chem. Biol. 4*, 674−681.

(25) Wallach, T., and Kramer, A. (2015) Chemical chronobiology: Toward drugs manipulating time. *FEBS Lett. 589*, 1530−1538.

(26) Hirota, T., Lee, J. W., Lewis, W. G., Zhang, E. E., Breton, G., Liu, X., Garcia, M., Peters, E. C., Etchegaray, J. P., Traver, D., Schultz, P. G., and Kay, S. A. (2010) High-throughput chemical screen identifies a novel potent modulator of cellular circadian rhythms and reveals CKIalpha as a clock regulatory kinase. *PLoS Biol. 8*, e1000559.

(27) Hirota, T., Lee, J. W., St. John, P. C., Sawa, M., Iwaisako, K., Noguchi, T., Pongsawakul, P. Y., Sonntag, T., Welsh, D. K., Brenner, D. A., Doyle, F. J., 3rd, Schultz, P. G., and Kay, S. A. (2012) Identification of small molecule activators of cryptochrome. *Science 337*, 1094−1097.

(28) Hirota, T., Lewis, W. G., Liu, A. C., Lee, J. W., Schultz, P. G., and Kay, S. A. (2008) A chemical biology approach reveals period shortening of the mammalian circadian clock by specific inhibition of GSK-3beta. *Proc. Natl. Acad. Sci. U. S. A. 105*, 20746−20751.

(29) Miller, M., Song, Q. X., Shi, X. L., Juenger, T. E., and Chen, Z. J. (2015) Natural variation in timing of stress-responsive gene expression predicts heterosis in intraspecific hybrids of Arabidopsis. *Nat. Commun. 6*, 7453.

(30) Masri, S., Cervantes, M., and Sassone-Corsi, P. (2013) The circadian clock and cell cycle: interconnected biological circuits. *Curr. Opin. Cell Biol. 25*, 730−734.

(31) Yao, Z., Petschnigg, J., Ketteler, R., and Stagljar, I. (2015) Application guide for omics approaches to cell signaling. *Nat. Chem. Biol. 11*, 387−397.